DESIGNING A U-STYLE MOORING FOR USE WITH CURRENT METERS

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THESIS

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WITH CURRENT METERS

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ABSTRACT

A study was conducted to select and design the optimum mooring system for positioning a three-instrument current meter array in 1800 feet of water off the California coast. A U-style mooring system was selected; the U-style mooring isolates the instruments from surface waves and offers three separate methods of instrument recovery. The mooring was designed and the various components to be used in its construction were specified. Computer analysis was used to approximate the theoretical static profile of the instrument array under the influence of current. An array of two instruments was stationed in 47 fathoms in Monterey Bay to test the basic design of the system. The mooring system was found to be suitable for safe and efficient deployment and recovery from R/V ACANIA.

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I. INTRODUCTION AND BACKGROUND

Early in 1972 it was decided to station a current meter array off the California coast to gather information on the California Countercurrent. The array was to be implanted in the summer of that year and was to have an on-site time of approximately one month. No specific location was specified; an on-site depth of 300 fathoms was suggested to ensure that the array could easily be stationed, relocated, and retrieved. This depth contour is close (less than 30 nautical miles) to the California coast between Big Sur and the Santa Barbara Channel. The shelf is overlain by the countercurrent in many places since the countercurrent tends to stay near the coast. The array would consist of three AANDERAA current meters positioned 160, 640, and 1140 feet (50, 200, and 350 meters) below the sea surface. The purpose of this thesis is to select and design the mooring which would accomplish this task. As an integral part of this report, a smaller mooring would be implanted in Monterey Bay to test the design features of the mooring, to test the operation of the meters, and to give Naval Postgraduate School personnel experience in implanting and retrieving the type of mooring system selected.

II. PRELIMINARY DESIGN CONSIDERATIONS

A. DESIGN REQUIREMENTS

The instrument array had to be constructed to meet certain design requirements.

As mentioned previously, the current meters were to be positioned at the 160, 640, and 1140 foot depths. The water depth at the array site was to be approximately 300 fathoms.

The current meters that were to be used imposed certain mechanical limits on the array configuration. These limits were specified in the technical manual for the AANDERAA current meters:

- The instrument spindle tilt had to be kept within 20° of vertical for optimum operation. It could not be tilted more than 30° from the vertical in any case.
- The spindle on the instrument was designed to withstand a mooring force of 4410 pounds (2000 kilograms).
- The instruments would have to be kept reasonably steady in the current stream.
- There could be no interference from mooring lines on the rather large direction vanes.

The entire array had to be capable of being safely transported, implanted, and retrieved by the Naval Postgraduate School's research vessel R/V ACANIA. Also the array would have to be economical. As much equipment as possible was to be drawn from NPS stocks to keep the purchase requirements for the design low.

B. RESEARCH FOR THE MOORING DESIGN

A review of the methods used by other oceanographic institutions in constructing moored instrument arrays indicated that these designs fell into two basic categories: the taut line systems and the slack line systems. A taut line assumes a straight vertical line in the absence of environmental forces. A slack line assumes an upward or downward catenary if the mooring cable has positive or negative buoyancy with respect to seawater.

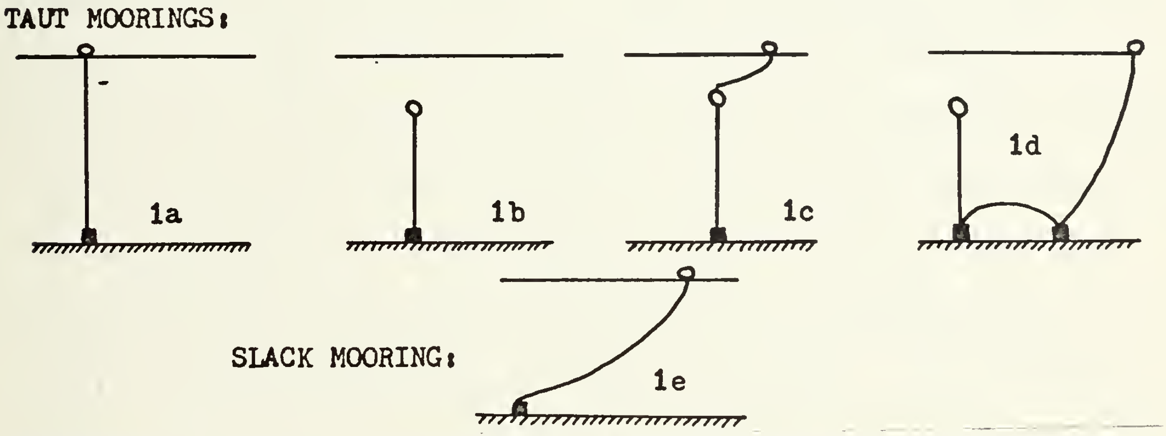

FIGURE 1 - SEVERAL TYPES OF MOORINGS WERE CONSIDERED FOR THE CURRENT METER ARRAY.

1. Taut Moorings

Buoy systems which incorporate a taut mooring have been used extensively in oceanographic work. Two basic types of taut line buoy systems have been used in the ocean: single buoy systems and multiple buoy systems. In the single buoy systems a taut line runs from the anchor to a subsurface or surface buoy. In multiple buoy systems a taut line runs from the anchor to a subsurface buoy which is joined by another line to a surface or another subsurface buoy. Examples of taut line systems are shown in Figure 1.

a. Single Buoy Systems

Figure 1a - This system has been used with success by Woods Hole Oceanographic Institution [Berteaux and Walden, 1969] and by Scripps Institution of Oceanography [Isaacs, et al, 1965; Sessions and Brown, 1971]. It is designed such that the synthetic mooring cable has an unstretched length less than the depth of the sea where the system is to be stationed. The cable is stretched between the surface float and the anchor and remains taut at all times. In the early 1960's Scripps designed and implanted systems of this type as an improvement over the type of system that had been in use since the early 1950's (the old type is represented in Figure 1c). Nylon line was used as the mooring cable. The surface float was of a catamaran design since it was less attractive and more difficult to steal than the old style decked-over skiff. In the final stages of modification this system was capable of maintaining station without failure for six months [Isaacs, et al, 1965]. Surface weather data and subsurface temperature data were obtained with these moorings. In the late 1960's Scripps used moorings of this type in the North Pacific and demonstrated that it was possible to keep these arrays operating successfully for periods of over one year and to have them withstand the stormy open-ocean conditions of the North Pacific [Sessions and Brown, 1971].

Figure 1b - This is the simplest of the single buoy taut line systems. The instrumented mooring line is kept under constant tension between the anchor and the

subsurface buoy. This system has been used by the U.S. Naval Oceanographic Office as a permanently installed deep water environmental monitor [Rooney, 1967]. Data was transmitted to shore by a coaxial cable that ran down the mooring wire from the instruments. Another system of this type, more directly applicable to the AANDERAA current meters, was the installation employed in the Strait of Gibraltar by the SACLANT ASW Research Center [Frassetto, 1966]. Internally recording current meters were suspended by the mooring system and were recovered by a time-delay anchor release.

b. Multiple Buoy Systems

Figure 1c - The system illustrated here has been used by Scripps [Isaacs, et al, 1963]. The taut line between the anchor and the subsurface buoy was a high tensile strength cable. The line between the submerged buoy and the surface float was a slack light nylon line. As mentioned earlier, the surface float was a decked-over skiff. Problems were encountered with this system; the slack pennant was cut and fouled by surface ships and the skiff was stolen.

Figure 1d - This is one of the newer types of mooring systems known as the U-mooring. One of the earliest uses of the U-mooring was by the Russians [Shirei, 1955]. Their Interdepartmental Oceanographic Committee designed and constructed "MOK" current meter arrays in the U-mooring style. Wire rope and synthetic line were used. More will be said of their mooring systems when techniques for implanting and retrieval are discussed. This type system has also been used by the U.S. Public Health Service in Lake Michigan

[Farlow, 1964], by Oregon State University in the Pacific [Pillsbury, et al, 1969], and by the Japanese in coastal waters [Hawes, 1968].

Common to all U-mooring designs is the groundline that runs between the two anchors of the mooring. This groundline can be used to snag a grapple if this means of recovery is required. The U-mooring makes use of taut line and slack line mooring techniques in one system. The taut line is used for the instrument array; the slack line is used for the marker float.

The concept of combining a taut mooring system with a buoyant grapple line has been used to advantage by the U.S. Navy. The U.S. Naval Civil Engineering Laboratory's Submersible Test Units (STU) were equipped with a long grapple line laid out above the sea floor [Jones, 1965]. The buoyant groundline connected the anchor of the subsurface taut line buoy to the test unit, as shown in Figure 1f. The inverted catenary could snag a grapple suspended

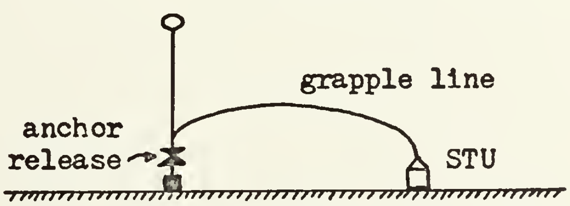

FIGURE 1f - A GRAPPLE LINE IS DESIGNED INTO THE STU MOORING SYSTEM.

from the recovery ship if the automatic release failed to separate the taut line from the anchor. The release mechanism failed in three out of the first three STU mooring systems and the grapple line, where it was used, enable recovery of the test units.

2. Slack Moorings

This is the traditional method of mooring buoys used for navigation aides and other markers. The mooring cable is cut from 1.5 to 2.0 or more times the depth of the sea. The surface buoy is free to float about on the end of this tether. A typical slack mooring system is shown in Figure le.

An example of a slack mooring is the NOMAD (Navy Oceanographic Meteorological Automatic Device), designed at Woods Hole. With this system a meteorological buoy has been moored in 10,800 feet of water in the Gulf of Mexico [Smith, 1965]. The buoy was moored to an anchor with a mooring cable composed of 10,000 feet of polypropylene line and 5,000 feet of dacron line. This concept of combining two synthetic lines into a single cable will be examined in detail later in this report.

C. SELECTION OF A MOORING SYSTEM

The system selected had to provide a platform on which to mount the current meters and had to conform to the design requirements listed earlier. Some of the systems described above were much better suited than others. The slack mooring was eliminated immediately because of the large angles in the mooring cable which would be harmful to the current meters. This defect of large angles could be corrected to some degree by hanging weights on the mooring cable beneath the current meters. However, the slack mooring would still be unsuitable for a current meter array since the meters would have considerable freedom to wander about as the

slack mooring changed orientation with changing currents and surface winds. As the meters move through the water there would be a degradation of current information recorded by the instruments.

The taut line systems were examined and their advantages and disadvantages were compared.

1. Contrasting the Single and Multiple Buoy Taut Line Systems

Single buoy systems are economical and easy to implant, but they have some disadvantages. The system shown in Figure 1a is coupled to the surface waves by the surface float; an elastic mooring line might not be able to absorb enough energy to isolate the uppermost current meter from the surface movement. It has the further disadvantage of being totally dependent on the surface float for survival of the system. If the float were lost or stolen the system would sink and might be lost. The arrangement shown in Figure 1b keeps the meters away from surface wave influence; however, once again the system is dependent upon a single float. There is also some danger of the system being unrecoverable if there is a failure in the remote anchor release. An automatic release is necessary because the system cannot be simply hauled aboard intact since the buoy is not immediately accessible from a surface ship. Search sonar and scuba divers could locate and enable recovery of this system if the release should fail. But search sonar is not always immediately available and there is some risk to using

divers. A groundline could be used for recovery purposes to improve this system.

Multiple buoy taut line systems are more difficult to implant and retrieve and are more expensive than the single buoy systems. However, they offer some compensatory advantages. The system shown in Figure 1c has the away-from-the-surface advantage of that shown in Figure 1b as long as the surface marker float is small enough to not affect the lower portion of the mooring. If the float is large the pennant line must be elastic enough to isolate the top of the taut mooring from the surface motions of the marker float. The system depends on the single subsurface buoy to support the instruments; one or more additional subsurface buoys may be attached to the taut line for redundancy in support. The surface marker is vulnerable and if it is lost the system would be dependent upon a mooring release for recovery. This system would be very useful for the array design if alternate means of recovery were available.

The U-mooring shown in Figure 1d combines the advantages of a subsurface buoy taut line mooring with a proven backup recovery system. One or more additional buoys may be attached to the taut line to provide reserve buoyancy in the event of failure of the top buoy. The taut portion of the mooring is not coupled to the surface with a pennant line, eliminating concern of wave motion contaminating the record. This system is complex from the viewpoint of implanting and recovery and is more expensive than the systems illustrated in Figures 1a, b, and c because of the extra mooring cable required.

2. Selecting the Mooring Design

The U-mooring appeared to be the most promising design for stationing the three AANDERAA current meters off the California coast. The main advantage of this design was that the instrument array on the taut line was not directly coupled to disturbing surface forces. An additional advantage was the availability of three recovery methods: an automatic release on the taut line leg, a surface marker and pennant which could be used to pull the array aboard, and the bottom grapple line which could be used as a last resort to recover the instruments. The cost of the extra line and anchor for the U-mooring was much less than the value of the instruments that might be lost if the additional recovery methods were not available. Implanting the array from ACANIA might be a complicated operation, but it was felt that with proper planning and preparation the operation could be performed safely.

III. PHYSICAL DESIGN OF THE ARRAY

Having selected the basic configuration of the array, the next step in the design was to specify the components necessary to build the array and to ensure that these components could be assembled into a complete system. In the interest of economy as much equipment as possible was to be drawn from Naval Postgraduate School stocks. The three current meters were already on hand (see Appendix A for a description of these meters). Other necessary components to be chosen were subsurface buoys, an automatic release of dependable design, and enough mooring cable, hardware, and anchors to build the system.

A. SUBSURFACE FLOATS

Naval Postgraduate School possessed several aluminum buoys, two of which had been successfully used on previous moorings. The buoys had been built to Naval Postgraduate School specifications and were designed to withstand an immersion depth of 1000 meters, a depth much deeper than planned for this array. Appendix A describes the design characteristics of these buoys.

B. MOORING RELEASE

The design of a mooring system is strongly influenced by the reliability of the release mechanism. Therefore, the dependability of various remote release devices was examined. Late in 1969 the National Oceanographic Instrumentation

Center (NOIC) undertook a study of remote release devices. It accumulated data on more than 200 deployments of 70 individual release mechanisms [NOIC, 1970]. These releases fell into three basic categories: corrosive releases, mechanical releases (time and pressure releases), and acoustical releases. The corrosive releases investigated had a built-in uncertainty as to when the actual release would take place. The corrosive process is highly dependent on water temperature and salinity. For example, a corrosive release with a delay time of 30 days has a 2.5 day (eight percent) uncertainty as specified by the manufacturer. The mechanical time releases had problems in the clock mechanisms. When they did function correctly, they released the mooring from the anchor to be buffeted by whatever sea surface conditions were present at the time of release. Acoustical release mechanisms, the most complex type used, proved to be the most reliable release mechanisms studied. However, a certain number of these failed to function upon command.

Naval Postgraduate School owned several mechanical time releases, but as discussed before these releases are not as reliable as the acoustical type. Therefore, in the interest of increasing the probability of a successful recovery an acoustical release was specified for the system.

Due to the high cost of the acoustical release, provisions were made for an alternate design which would utilize one of the on-board mechanical time releases. The design specifying an acoustical release exclusively was denoted Type I (Figure 2). Another design, denoted Type II (Figure

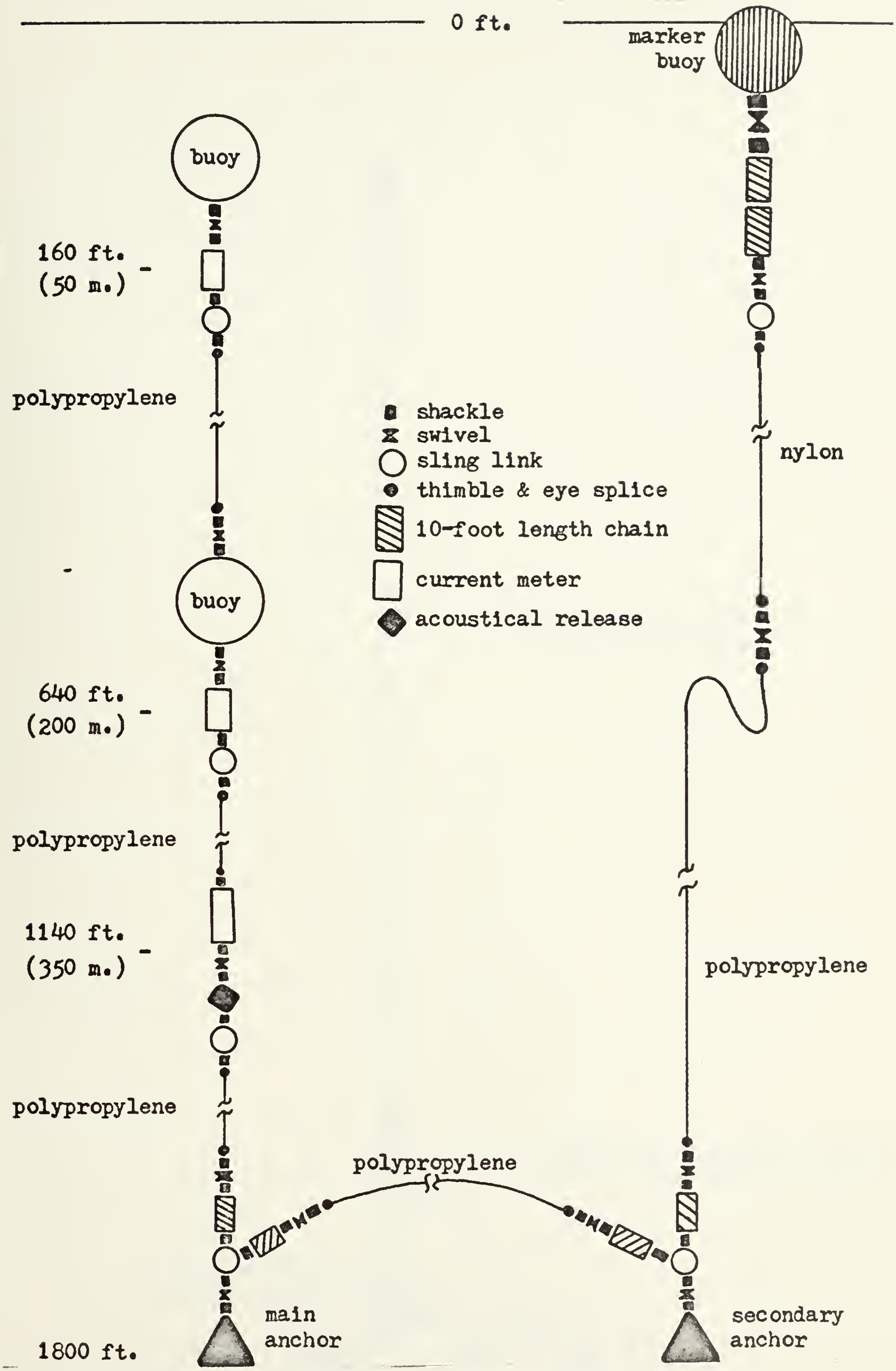

FIGURE 2 - TYPE I MOORING

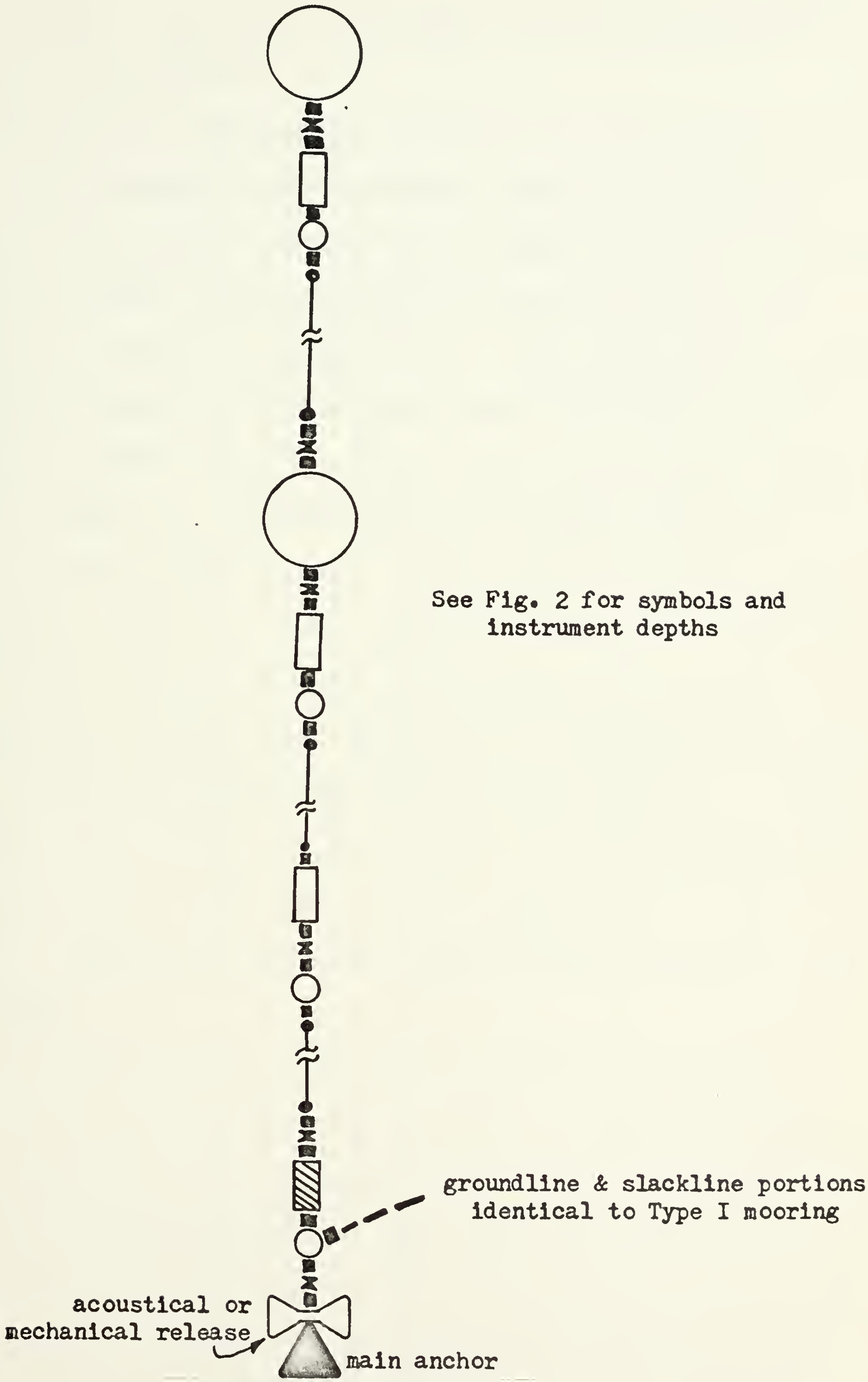

FIGURE 3 - TYPE II MOORING

3), could use either an acoustical release or a mechanical time release. Appendix A discusses the two different releases in some detail.

In the Type I system the release is designed to be just below the bottommost current meter. When the acoustical release is actuated by command, the upper portion of the taut mooring detaches itself completely from the rest of the mooring and floats to the surface. There is no need to keep the array secured to the bottom since the release is triggered by a coded acoustic command from the recovery vessel when the ship is on station prepared to make immediate recovery of the current meters. The remainder of the mooring (groundline, anchors, slack line and marker buoy) could be recovered separately by pulling the marker buoy aboard or by grappling if the marker were gone. By placing the acoustical release just below the third current meter it is about 600 feet closer to the surface than if it were placed just above the anchor. This puts the release closer to the acoustic triggering source and improves the reliability of the release.

The surface marker slack line is the primary means of recovery for the Type II system. When the mechanical time release is used in this system it is viewed as a backup system of recovery because of the less-than-complete reliability of the timer mechanism. This design incorporates a provision for preventing the mooring from drifting away if the mechanical release operates prematurely. The mechanical release is positioned on the mooring such that

when the release is triggered that portion of the mooring from just above the taut line anchor to the uppermost subsurface buoy would be still attached to the groundline. The subsurface buoys would pull the array to the surface and the array would be held in position by the secondary anchor. In this mode of recovery the taut line anchor would be lost. The Type II mooring design maintains positive control over the taut portion of the mooring once release occurs. Unlike the Type I system the subsurface buoys and current meters are not free to drift away after release triggers. When a reliable acoustical release is in the Type II mooring system, it can be considered the primary means of recovery.

C. MOORING LINES

A choice existed among several kinds of mooring lines. Natural fiber line was eliminated since it could suffer severe deterioration in the 30 days that the system was expected to remain on station. Wire rope, synthetic line, or a combination of wire rope and synthetic line could be used. The following section discusses the advantages and disadvantages of each type of line and the considerations that led to the selection of synthetic line.

1. <u>Comparison of Wire Rope and Synthetic Line</u>

The selection of the type of line was governed by the following characteristics [Tudor, 1967]:

- Strength versus diameter: wire rope is superior to synthetics (nylon, dacron, polypropylene, mylar, etc.). Nylon line, one of the strongest synthetics,

has about one-fourth of the strength-to-diameter ratio as a wire rope of the same diameter.

- Handling: synthetics are more easily thrown around a capstan, stowed, and spliced. Winching is easier with synthetics but caution must be exercised to avoid overheating of the line. Wire rope is more difficult to handle but does not overheat during normal handling. Synthetics can be used on a capstan but wire rope requires a winch drum for proper handling.
- Buoyancy: positively buoyant synthetics such as polypropylene permit smaller buoys and upward curved catenaries (desirable for the groundline portion of the U-mooring). Wire rope is negatively buoyant.
- Kinks and bights: wire ropes are susceptible to these problems which can result in failures of mooring systems. Flexible synthetic line is less susceptible to kinking and forming bights.
- Twisting: during the period of being lowered under tension a wire rope or synthetic line stretches. The cable has a tendency to unlay, or twist, as it stretches. A release of the tension on the line results in a torsional inbalance. If the release of tension is faster than the line's ability to return to its normal shape there might be a snarl of the strands of the line.

- Stretch: wire ropes normally elongate less than five percent under load. Synthetics elongate between 10 and 15 percent under a working load. When a shipboard winch lowers a taut mooring under a heavy strain the line slackens when the anchor reaches the bottom. This sudden slack may snarl the entire system due to the torsional inbalance discussed above. This problem is found in both layed wire rope and layed synthetic line.
- Corrosion: wire rope suffers from this weakness, but synthetics are highly resistant.
- Marine life effects: synthetic line appears to hold an attraction for fish. Moorings have been damaged and have failed due to fishbite. The recorded fishbite failures have mostly occured in warm water areas at depths extending to 6000 feet. Fishermen know that fish will attack bright colors and shiny objects. Dark colored mooring lines and dull-finished metal fittings might be useful where there is danger of fishbite.

2. <u>Choice of Polypropylene Line</u>

The buoys available for the array were small (about two feet in diameter) and had limited buoyant force (159 pounds each, see Appendix A). Therefore, the type line for the taut portion of the mooring had to be both light and durable. One-quarter inch wire rope has an in-water weight of 0.1 pounds per foot. Based upon the taut line length of approximately 1600 feet, the necessary wire rope would weigh

approximately 160 pounds. This was more than half of the total buoyant force available if two buoys were used. Even if a substantial fraction such as 1/2 or 1/3 of the taut line portion of the mooring was composed of wire rope (to minimize fishbite damage risk or to adjust the elastic properties of the mooring) the weight would still present a problem.

The Naval Postgraduate School had previous experience with subsurface current meter arrays. Three-eighths inch diameter polypropylene line had been used with success in simpler designs. This synthetic line is inexpensive and durable. It is easy to handle and splice. Its greatest advantage is its slight positive buoyancy (specific gravity: .90) which would allow the cable of the taut portion of the mooring to be self-supporting. It would also make the groundline a better grapple target by giving it an upward curving catenary.

But as mentioned previously, synthetics do have some disadvantages which are shared by polypropylene line. A polypropylene line is not as strong as a wire rope of the same or even smaller diameter. For the design under consideration the largest static force on the mooring line would occur when the mooring anchors were being lowered through the sea. The line would have to withstand the in-water weight of an anchor and other components. However, the estimated loads would be well within the stress limitations of 3/8" polypropylene line since the system is designed to use relatively lightweight anchors.

Another potential problem which had to be considered when using polypropylene line was its tendency to heat and fuse on the capstan when under high stress. This problem had been met and solved in the past by the U.S. Navy while implanting the Submersible Test Units by playing a stream of water onto the line as it was strained around the capstan. Once again, the relatively small stresses in the Naval Postgraduate School mooring would help to keep this problem to a minimum.

An unfortunate feature of both synthetic line and wire rope is the tendency for a lay-constructed rope to twist and unlay as it is relaxed from a stressed state. This problem can be overcome by the liberal use of swivels in the system and by the use of braided vice layed line. In the past NPS has used lay-constructed line and swivels with no serious problems. Braided line is more expensive and harder to splice than lay-constructed line. It was felt that a layed line could be used if stresses were kept low and swivels were used in the design.

Polypropylene line has also shown a tendency to creep in certain circumstances. There are conflicting reports on the creep behavior of polypropylene line in seawater. In general, if the applied loading on polypropylene line is kept below about one-fifth of the tensile strength of the line there should be little problem with the creep process. For three-eighths inch polypropylene line one should start to worry about creep when a steadily applied load increases above 500 pounds.

As previously mentioned, synthetic line is susceptible to fishbite damage. This vulnerability is inherent to all types of synthetic line. Care must be taken to ensure that a mooring constructed of synthetic line will survive this type of damage. There is a considerable store of practical knowledge about fishbite damage. In the late 1950's and early 1960's Woods Hole studied this problem in the warm waters around Bermuda and in the Gulf Stream [Stimpson, 1964]. Cuts on polypropylene line which could have been the result of fishbite occured at depths to 1200 meters. Damage varied from little nibble marks to clean bite-cuts through 9/16" line. Scripps has encountered some biological damage to their moored systems off the Pacific coast [Isaacs, et al, 1965], but the problem seems to be less severe than found in the Atlantic. In one case a mooring was recovered with a dead shark entangled in the line. A broken shark's tooth was imbedded near the end of a parted line in another case. In still another a line was found to have long razor-like slashes along its length to a depth of 200 feet. Scripps used white and gold colored line in this series of moorings consisting of twenty-two installations of the catamaran surface float type.

Some of the latest arrays installed by Scripps in the Pacific Ocean have encountered fishbite damage [Sessions and Brown, 1971]. One station located in the Central East Pacific was recovered due to fishbite damage after only three months. Numerous cuts and slashes were observed in that portion of the mooring cable between 600 and 1000 feet.

Pieces of shark teeth were removed from the cable jacket. Another station about 800 miles further north suffered much less biological damage in the 18 month period that it was deployed.

Sharks sometimes appear to strike at any object that attracts their attention. A small float on a line, a tag end of a line, and loose pieces of tape on instrument cables have all been damaged by sharks in buoy anchorage systems [U.S. Naval Civil Engineering Laboratory, 1965]. There has been some speculation that biological growths on mooring cables attract fish. The fish attempt to eat the growths on the cable and damage the cable in their attempts.

Because of the relative infrequency of fishbite damage to previous installations along the Pacific Coast, it was felt that a moored system consisting of light colored synthetic line could survive the fishbite threat for an on-station time of one month in the general geographical area of the Santa Barbara Channel or Monterey Bay.

Polypropylene line has been proven to be very durable in seawater. The following examples demonstrate that long immersion under high pressure affects neither the buoyancy nor the strength characteristics of polypropylene line [Jones, 1965]:

- A piece of one-inch diameter polypropylene line was exposed for over 600 hours to a hydrostatic pressure of 10,000 psi in a pressure vessel. The line retained its buoyant characteristics.

- Two specimens of one-inch diameter polypropylene line were tested to failure after having been exposed to the deep ocean environment at 5600 feet for 123 days. The samples were about as strong after the exposure as before. There was less than ten percent loss of strength from nominal advertised values.

Having considered the advantages and disadvantages of synthetic line and placing emphasis on the fact that lay-constructed polypropylene line had been used by NPS with success in previous moorings, it was decided to construct the major portion of the mooring with lay-constructed polypropylene line.

Lay-constructed nylon line was also specified for a portion of the system, i.e. the slack moored marker buoy line was to be a combination of half polypropylene line and half nylon line. Polypropylene line has a slight positive buoyancy; nylon line has a slight negative buoyancy. If the entire marker buoy line were to be polypropylene, it might rise and lie along the surface under conditions of slight current and low windspeed. This would expose the line to the screws of passing ocean traffic and could mean the loss of the marker buoy. If the upper portion of the line were nylon, however, the cable would assume the profile shown in Figure 4, and possible surface damage would be avoided [Isaacs, et al, 1963]. The buoyant polypropylene lower portion would be self-supporting and would prevent the lower portion of the line from dragging along the sea bottom as

the surface buoy moved about. This concept has been successfully used in the NOMAD buoy system where the upper portion of the mooring cable was dacron and the lower portion was polypropylene line [Smith, 1965]. The "S" shape formed by the two lines tends to reduce surface excursion and absorb shock forces in turbulent conditions.

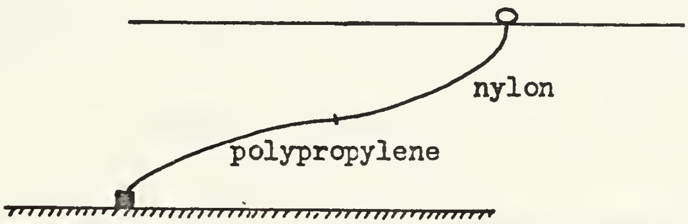

FIGURE 4 - TWO TYPES OF SYNTHETIC LINE ARE USED IN THE SLACK LINE.

Appendix A contains detailed information on the polypropylene and nylon line chosen for the mooring.

3. Line Lengths

The lengths of line required for the taut portion of the mooring are discussed in the Conclusions section of Appendix B. For the slack moored marker buoy line, employing a deep-water line length-to-water depth ratio of 1.8 indicates that 3200 feet of synthetic line are required for the 1800 foot (300 fathom) specified water depth. This slack marker line would consist of 1600 feet each of nylon and polypropylene line. Both segments of line would be 3/8" lay-constructed line with approximately equal working loads.

The length of groundline was determined by considering the navigational accuracy expected upon returning to the site if the marker buoy were missing and the acoustical or mechanical release malfunctioned making grappling necessary. Knowing the line of bearing between the two anchors (recorded during implanting operations), the recovery vessel

would drag a grapple perpendicularly across this line of bearing. If navigational accuracy is assumed accurate within 500 yards (a conservative estimate) the ship would navigate to a position midway between the two anchors and drag for the groundline. Past experience indicated that a groundline 1000 yards in length provided a good chance of grapple recovery (Figure 5). Oregon State University used a groundline

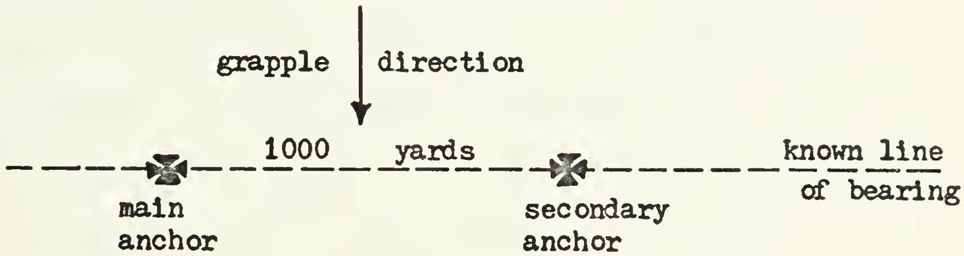

FIGURE 5 - THE GROUNDLINE LENGTH IS CHOSEN TO HELP ENSURE A SUCCESSFUL GRAPPLE RECOVERY.

of at least 990 yards (900 meters) in length for their U-moorings. They obtained successful retrievals on the four occasions that they had to grapple to recover their array [Pillsbury, et al, 1969].

The long groundline specified above may seem wasteful. However, it enhances the chance of recovery of the entire mooring system. Also the low stresses in the mooring cables should not damage the line and care in implanting and recovery should prevent chafing and pinching permitting reuse of the line for later projects.

D. HARDWARE

The use of galvanized steel fittings for the small hardware (chain, shackles, swivels, sling links, thimbles) would be permissible since the mooring was designed to be in the

sea for a relatively short period of time. Appendix A contains detailed descriptions of the hardware components that were to be used in the mooring system.

The shackles should be of the screw-pin type. Experience had shown that the shackle pins must be wired in place to prevent them from unscrewing and falling out due to the motion of the mooring.

On the taut portion of the mooring at each discontinuity in the synthetic line a swivel was designed into the system. Swivels were also included on the ends of the groundline and on the ends and middle of the slack line portion of the mooring (Figures 2 and 3). The swivels would help to combat any tendency for the line to kink and unlay as it relaxed from the stressed state.

The sling links were included into the system to afford points of attachment for lengths of stopper cable. Provision for the attachment of a stopper cable is necessary to allow the individual buoys and instruments to be removed from the mooring during recovery. The stopper cable would hold the dry end of the cable out of the water while the various components are unshackled.

Short lengths of chain were included as part of the mooring cable near the anchor. This chain would prevent the synthetic line from chafing against the anchor or being cut if the anchor were to roll onto it.

Hardware deterioration due to corrosion had to be considered. In past moorings designed and used by Woods Hole it was found that the pins and bodies of shackles subjected to

motion and corrosion in the sea were severely pitted. Their original size was reduced as much as 30 percent after 300 days of immersion [Berteaux and Walden, 1969]. Chain sections subjected to abrasion and corrosion near the mud bottom had as much as a 54 percent reduction in strength after 254 days of immersion. Linearly pro-rated, this would indicate a reduction in strength of the shackles of three percent per 30 days and of chain about 6.4 percent per 30 days. There is much imprecision in such an estimate since the corrosion process may not be linear with the passage of time, e.g., as an oxidized coat forms the process slows. Abrasion, however, could probably be reasonably estimated in that manner. An allowance was made to account for a more rapid corrosion in the first 30 days than would be indicated by pro-rating the data above. Design values of reduction in strength of five percent (for shackles, swivels, and sling links) and eight percent (for chain) were arbitrarily used for the 30 day immersion period. This is probably a conservative estimate since the data selected for the estimate reflected the most severe material deterioration found by Woods Hole.

In any project of this nature, prior to going to sea, the various hardware components should be physically fitted together to ensure that shackles will fit sling links, chain links, swivels, etc. Time and trouble will be saved when the system is assembled and implanted.

E. ANCHORS

Two separate anchors are required for the U-mooring: one at the bottom of the taut line section and the other at the bottom of the slack line to the marker buoy. The required weights of these anchors depend upon the forces expected on each due to buoyancy and drag. There is no requirement for specialized types of anchors; mass anchors such as concrete filled drums or old engine blocks chained together suffice. Concrete anchors are relatively inexpensive, but have the disadvantage of a high in-air weight. Scrap iron weighs less in-air for a certain required in-water weight, however it costs more than the concrete anchors.

A computer analysis was made of the forces in the taut mooring due to buoyancy and drag (Appendix B). Under the maximum current profile considered (i.e., 1.2 knots at the surface to 0.2 knots at the bottom) the horizontal and vertical forces on the anchor of the taut portion of the mooring were found to be 80.5 and 138 pounds, respectively. Scripps has used the following rule of thumb in designing their buoy systems: the net vertical reaction against the bottom must be at least 1.4 times the sum of the expected horizontal forces [Isaacs, et al, 1963]. This has led to satisfactory performance of their anchors on relatively flat bottoms. Using the above rule, the required in-water anchor weight (W_a) for the mooring under consideration is:

$$W_a - 138 = 1.4(80.5)$$

$$W_a = 250 \text{ pounds (approximately)}$$

The in-air weight is greater and depends on the anchor construction; for the concrete-filled cans described in Appendix A the anchor weight in air is approximately 460 pounds. This anchor is denoted as the main anchor to distinguish it from the secondary anchor at the end of the slack line portion of the mooring.

In the Type I mooring the secondary anchor could be considerably lighter than the main anchor. It anchors only the slack moored marker buoy line and one end of the groundline. A 230-pound (416 pounds in-air weight) secondary anchor was specified for the Type I mooring. In the Type II mooring the secondary anchor would not only have to hold the above lines but it would also have to hold the taut line assembly after the acoustical or mechanical release had functioned (Figure 6). A 285-pound (520 pounds in-air weight) secondary

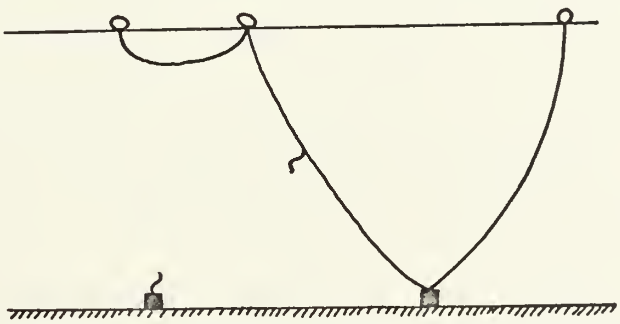

FIGURE 6 - THE ANCHOR AT THE END OF THE SLACK LINE SECURES THE ARRAY AFTER RELEASE HAS OCCURED IN THE TYPE II MOORING.

anchor was specified for the Type II mooring. Sizing of the secondary anchors was based on previous practical experience. The secondary anchors are described in detail in Appendix A.

One important factor that had to be considered when the sizes of the anchors were determined was the weight handling capability of the winch aboard ACANIA. For simplicity the anchors were to be handled by the hydrographic winch aboard the ship. This winch operated safely when it handled weights no heavier than about 500 pounds. The heaviest anchor weight specified for the mooring system was the 520-pound secondary anchor for the Type II mooring system. This anchor weight was considered within the safe working capability of ACANIA's hydrographic winch.

The use of relatively lightweight anchors is advantageous since the largest static force on the mooring cable occurs as the anchors are lowered to the bottom. For the Type I mooring the main anchor would subject the synthetic line to the greatest static force. The secondary anchor would be critical in the Type II mooring. Figure 7 illustrates the maximum static line loadings for the Type I and II mooring systems. These loadings would be less than the working strengths (450 pounds for polypropylene, 410 pounds for nylon) and far less than the rated breaking strengths (2,700 pounds for polypropylene, 3,700 pounds for nylon) of the 3/8" synthetic line. The in-air weights of the anchors were not considered since the weights of the anchors would be supported by lengths of chain when the anchors are above water level.

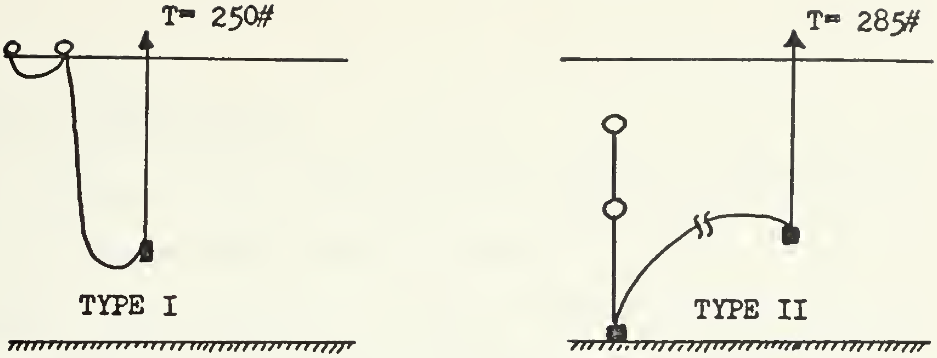

FIGURE 7 - MAXIMUM LINE LOADINGS DURING IMPLANTING DIFFER FOR THE TYPE I AND TYPE II MOORING SYSTEMS.

F. SURFACE MARKER BUOY

The surface marker buoy must be readily visible and relatively secure from loss by natural forces, theft, or vandalism. Additionally, it must present a minimal navigation hazard. A foam-filled buoy would be preferable to one constructed as a hollow shell. To discourage tampering by making the cable harder to cut a length of chain is used to attach the buoy to the slack mooring line (Figure 2). The marker buoy is critical in relocating the mooring unless a precise navigational system is available on the recovery vessel. Appendix A gives a description of the marker buoy.

G. LISTS OF MATERIAL REQUIRED

Table I lists the material required for mooring Types I and II. Appendix A contains descriptions of all components specified.

TABLE I - MOORING TYPES I AND II, MATERIALS REQUIRED

COMPONENT	REQ'D FOR TYPE I	REQ'D FOR TYPE II
AANDERAA Current Meters	3	3
AMF 280 Acoustic Release	1	1
		or
BRAINCON Type 422 Timed Mechanical Release	-	1
Aluminum Subsurface Buoys	2	2
Surface Marker Buoy	1	1
Main Anchor (250 pounds in-water)	1	1

Secondary Anchor (in-water weights)	1 (230 pounds)	1 (285 pounds)
3/8" Polypropylene Line	6256 feet	6256 feet
3/8" Nylon Line	1600 feet	1600 feet
5/16" Chain	60 feet[1]	60 feet[2]
3/8" Shackles	40 (approx.)[3]	40 (approx.)[4]
3/8" Swivels	13	13
1/2" Sling Links (round)	6	6
1/2" Sling Link (rectangular)	-	1 (for mechanical release)
Thimbles for 3/8" line	12	12

H. STRENGTH OF COMPONENTS

Table II lists the manufacturers' advertised strengths of the various components of the mooring designs.

TABLE II - STRENGTH OF COMPONENTS

COMPONENT	Strength in pounds: ULTIMATE	WORKING	WORKING, WITH ALLOWANCE FOR CORROSION[5]
AANDERAA Current Meters (Spindle strength)	4410	*	*
AMF 280 Acoustic Release (release capability)	1000	*	*
BRAINCON 422 Timed Release	8000	*	*
3/8" Polypropylene Line	2700	450	-

1,2,3,4 The actual amount depends on how the anchors are constructed. See Appendix A.

5 Allowances for corrosion after 30 day immersion: 5 percent for shackles and swivels, 8 percent for chain.

3/8" Nylon Line	3700	410	-
5/16" Chain	*	1750	1610
3/8" Shackles	12,000	2000	1900
3/8" Swivels	11,250	2250	2140
1/2" Sling Links	greater than 20,000	*	*

* Not Available

IV. AN EXPERIMENTAL SMALL-SCALE MOORING

It was felt that it would be prudent to assemble and deploy a small version of the Type II mooring in the shallow relatively protected waters of Monterey Bay before attempting the moorings described in Section III. The Type II mooring design with a mechanical release was chosen because the purchase of the acoustical mooring release could not be expected in the immediate future.

This test would permit several important factors to be more completely examined. First, the basic U-mooring design would be evaluated in terms of the Naval Postgraduate School's capability of constructing and implanting a system of this type with the resources available. Second, participating personnel would gain experience in working with a U-mooring system. Third, the equipment (current meters, mechanical release, subsurface floats, etc.) to be used in the full-scale mooring could be assembled and tested as a complete system and any component failures could be analyzed and corrected. Fourth, the solutions to any problems encountered in the small-scale mooring could be applied to the full-scale mooring.

The design for this experimental mooring is shown in Figure 8. It should be noted that this mooring placed only two current meters in the sea rather than the three meters of the full-scale mooring. The only other differences between this mooring and the full-scale Type II mooring were

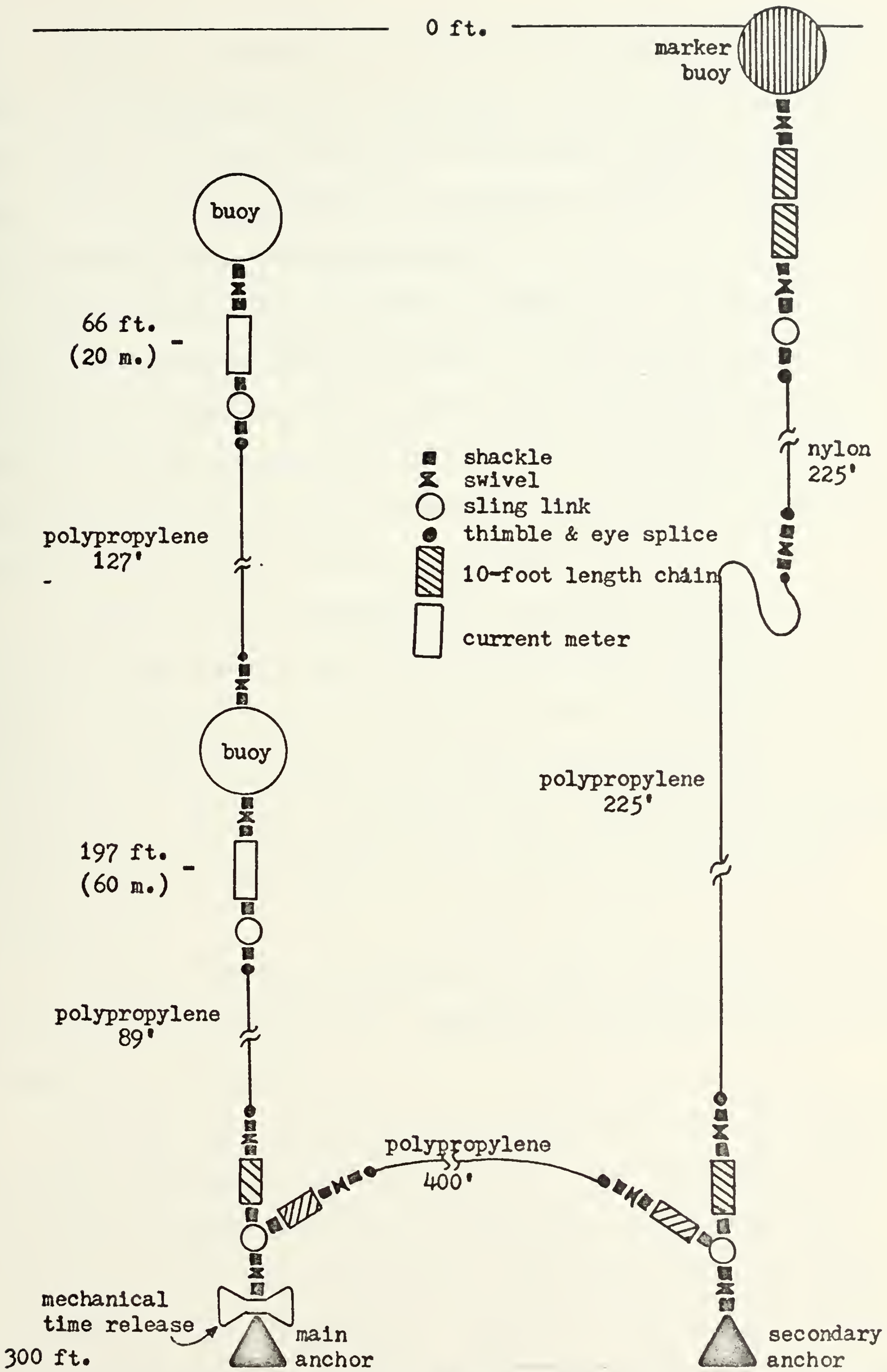

FIGURE 8 - A SMALL-SCALE MOORING WAS CONSTRUCTED FOR USE IN MONTEREY BAY.

the lengths of synthetic line used and the depth of the sea where the array was to be implanted. A depth of 300 feet was chosen to allow the array to be placed nearby in Monterey Bay. This shallow depth also enhanced chances of recovery if grappling were to be necessary.

Anchor sizing was purposely a duplicate of that in the full-scale Type II mooring design. This gave personnel experience in handling the weights which would be required in the full-scale mooring. Additionally, 60 pounds of lead were attached to the main anchor to compensate for the third current meter which was not installed.

A rather short groundline was specified because of the very high near-shore navigational accuracy available. Numerous landmarks were available for visual piloting in the southern part of Monterey Bay where the mooring was to be stationed. The short groundline also reduced the probability of the array being caught by the trawling of commercial fishermen.

A list of material required for this small-scale mooring is presented in Table III. Appendix A describes all of the components specified.

The small-scale mooring was preassembled in subsections to save time during implanting operations. Lines were cut to proper lengths and the line ends were terminated with eye splices and steel thimbles. The lines were then wound on wooden reels and labeled. Lengths of chain were precut and fitted with galvanized steel hardware as required. Anchor components were obtained and the anchor weights were carefully checked.

The subsurface buoys were pressure-tested by immersion at a depth of 1800 feet for 20 minutes. The surface marker float and the subsurface buoys were then painted and fitted with hardware.

Just before the mooring was deployed the current meters were started, sealed, and fitted with hardware. The mechanical time release was preset to release the mooring at 0600 on 27 July 1972.

Most of the shackle pins were wired in place; however, the pins on the shackles that would join the sub-sections were loosely installed. These would be tightened and wired as the mooring was assembled aboard ship. All lines and hardware were rechecked for soundness. The preassembled sub-sections were loaded aboard ACANIA.

The small-scale mooring was implanted in Monterey Bay at coordinates 36°42.2 N, 121°54.2 W on 13 July 1972. The next section discusses the actual implanting and retrieval procedures used. Any anticipated differences from the procedures to be used for the full-scale mooring are included in the discussion.

TABLE III - SMALL MOORING, MATERIALS REQUIRED

COMPONENT	REQUIRED
AANDERAA Current Meters	2
BRAINCON Type 422 Timed Mechanical Release	1
Aluminum Subsurface Buoys	2
Surface Marker Buoy	1
Main Anchor (250 pounds in-water)	1
Secondary Anchor (285 pounds in-water)	1
3/8" Polypropylene Line	841 feet
3/8" Nylon Line	225 feet
5/16" Chain	60 feet[6]
3/8" Shackles	35 (approximately)[7]
3/8" Swivels	12
1/2" Sling Link (round)	5
1/2" Sling Link (rectangular)	1
Thimbles for 3/8" line	10

6,7 The actual amount depends on how the anchors are constructed. See Appendix A.

V. IMPLANTING AND RETRIEVAL TECHNIQUES

The success of any current meter array largely depends on how carefully the implanting and retrieval techniques are formulated and followed. This portion of the total system design could not be slighted. Alternate ways of accomplishing the task had to be considered and the best plan tailored to the capabilities of the NPS research vessel ACANIA.

A. PROVEN PROCEDURES FOR IMPLANTING THE MOORING

As mentioned earlier, the U-mooring has been used by other institutions. Each used a certain unique procedure to implant their mooring. It was of value to examine the various techniques.

In simplest terms there are two ways to deploy a U-mooring: first, the slack line portion of the mooring can be launched followed by the groundline and the taut line section; and second, the reverse can be done. Both techniques have been used with success.

1. Surface Marker Buoy First

The Russian Interdepartmental Committee developed an effective technique for implanting current meter arrays in one of the earliest uses of the U-mooring [Shirie, 1962]. The surface marker buoy was the first component of the system to be floated. The slack line portion of the mooring was then paid out and the secondary anchor was shackled onto the

line and put overboard. The groundline was then paid out and the main anchor was shackled to the end of this cable and put over the side. Instruments were suspended from the cable at premarked points as the taut portion of the mooring was lowered down. Finally the subsurface buoy was attached to the upper end of the taut line. When the main anchor rested on the bottom the winch hook was disengaged from the subsurface buoy by remote release. It was interesting to note that the Russians employed a short groundline so that both anchors were simultaneously suspended above the sea floor. The mooring cable had to withstand the combined weight of both anchors. Figure 9 illustrates this technique.

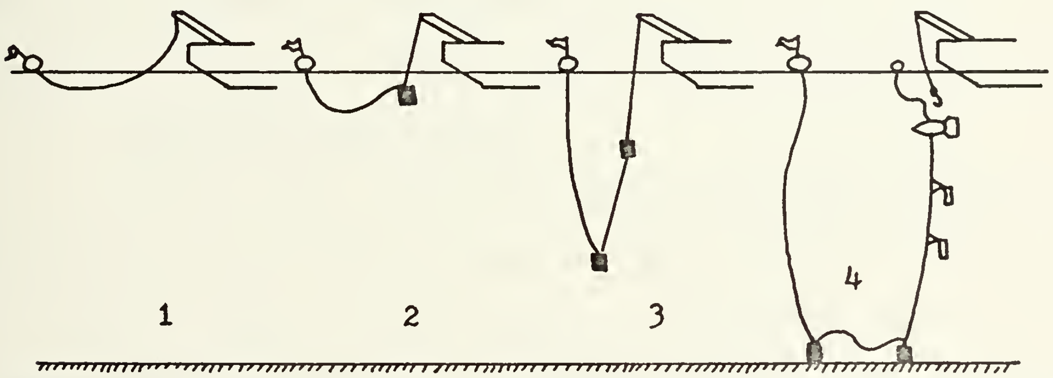

FIGURE 9 - THE USSR U-MOORING DEPLOYMENT PROCEDURE COMMENCED WITH THE LAUNCHING OF THE SURFACE MARKER BUOY.

Quite similar to the Russian procedure was the procedure used by the U.S. Public Health Service in Lake Michigan [Farlow, 1964]. The surface marker buoy (a meteorological buoy in this case) was the first component placed in the water. The marker buoy line was then paid out to its full length. The secondary anchor was suspended over the side and let go. It fell to the sea bottom, trailing the

groundline which was paid out freely by the ship. The bitter end of the groundline was attached to the main anchor but snubbed to the ship. The groundline went slack when the secondary anchor hit bottom. The main anchor was then swung over the side. Next the single subsurface buoy was suspended over the side and the instruments were put overboard in order beginning with the one closest to the subsurface buoy. The instrument line hung down in a "U" with no slack in the connecting lines. The subsurface buoy and the main anchor still remained at the surface. The groundline was unsnubbed from the ship and permitted to exert a strain on the main anchor. The main anchor was then let go and the instrument line followed the main anchor down. The subsurface buoy was released and the system was fully deployed.

2. Subsurface Buoy First

Oregon State University implanted their U-mooring in a manner which was opposite to that used by the Russians and the U.S. Public Health Service [Pillsbury, et al, 1969]. A subsurface buoy was put over the side first and the uppermost current meter was attached to the buoy. The taut line portion of the mooring was paid out as the ship moved away from the subsurface buoy. Additional current meters and floats were attached to the cable as the ship continued to move away from the first subsurface buoy. The end of the taut line portion was attached to the main anchor which was lowered into the sea by the groundline. The groundline was paid out under tension until the main anchor rested on the bottom. The ship then moved ahead on a predetermined bearing,

paying out the groundline which was attached to the secondary anchor aboard the ship. The secondary anchor was put over the side and lowered by the slack line portion of the mooring when the groundline was all paid out. Finally the surface marker float was attached to the slack line and set afloat.

3. Contrasting the Two Techniques of Implanting

The procedure employed by Oregon State had the very important advantage of having positive control in positioning the taut portion of the mooring. The ship could maneuver about, towing the floating taut line portion of the mooring, until it reached precise location or desired water depth. The first anchor down was the main anchor. In the implanting operations of the Russians and the U.S. Public Health Service the first anchor down and on the bottom was the secondary anchor. The ship was limited in maneuverability by being anchored to this secondary anchor via the groundline. If there were a serious error in calculating the depth (e.g., on a considerably sloping bottom) the secondary anchor might have to be hoisted clear of the bottom and moved to another location.

In terms of the effort required to implant the mooring the Oregon State procedure was superior to the Russian technique. Using the latter procedure, the most complex part of the mooring (the taut line portion with the meters and buoys) would have to be shackled together piece by piece as it was lowered into the water. In the Oregon State technique the entire taut line portion of the mooring

could be assembled in advance and put over the side as the ship moved away from the uppermost subsurface buoy.

From a safety viewpoint the Oregon State mooring deployment procedure was superior to that of the Public Health Service. In the former technique there were no free-running lines pulled off the deck by a rapidly sinking anchor as there were in the P.H.S. procedure. The Oregon State procedure retained positive winch control of both anchors until they rested on the bottom. Additionally there was no sudden shock on the instruments as there would be if a free-falling anchor pulled them down.

In the interest of safety, efficiency, and accurate positioning of the mooring, the implanting technique used by Oregon State was the preferred method of deploying the U-mooring. This general technique had to be tailored to ACANIA's capabilities.

4. Deploying the Mooring From ACANIA

The components of the small-scale mooring were on-loaded aboard ACANIA early in the morning of 13 July 1972. The ship got underway and arrived at the mooring site at 0930. The wind was westerly at five to seven knots; there was a slight northwesterly swell. Implanting operations commenced immediately upon confirming the depth of the sea to be 47 fathoms over a large area.

All assembly operations took place portside, amid-ships, on the main deck extendable platform. All winching was accomplished by the capstan on the hydrographic winch. This winch was on the boatdeck above and inboard of the main

deck platform. Running lines were passed through a large snatchblock shackled to an A-frame over the extendable platform. As the prepared subsections of the mooring were shackled together the shackles were safety-wired with stainless steel mousing wire.

Current meter 1 was shackled to the uppermost subsurface buoy. This assembly was shackled to the outboard end of the 127-foot length of polypropylene line. The line was spooled on a cable reel on the boatdeck; the line was free to pull off the cable reel as the reel rotated on a wooden spindle. The buoy and meter combination was placed in the water on ACANIA's windward side. The ship was allowed to drift away from the buoy and the line was let out.

A problem immediately developed when the buoyant polypropylene line wound around the current meter vane. The buoy and the meter were recovered, untangled, and a heavy shackle was placed on the line. The shackle was free to slide along the line, keeping a constant downward tension as the line was let out. This prevented the line from rising up and tangling on the meter. The buoy and meter were put back into the water and implanting operations resumed.

The ship drifted away from the buoy until the 127-foot line was paid out. The inboard end was shackled to the top of the second buoy. Current meter 2 was shackled to the bottom of this buoy. The outboard end of the 89-foot polypropylene line was shackled to the bottom of the current meter spindle. A heavy shackle was slipped onto the line

to maintain tension as before. The second buoy and meter combination was placed in the water and ACANIA drifted away from it.

The main anchor was joined to the mechanical release by running the anchor connecting chain through the release rectangular sling link. The swivel at the top of the release was shackled to the round sling link of the main anchor chain bridle. This bridle consisted of two 10-foot chains connected to a sling link. One leg of this bridle was shackled to the outboard end of the 400-foot polypropylene groundline which was spooled on a reel on the boatdeck. The other leg was shackled to the inboard end of the 89-foot polypropylene line. The groundline was bent around the capstan and a strain was taken on the main anchor. The anchor-release combination was lifted off the deck and lowered into the water.

Momentarily, the full in-air weight of the anchor was sustained by the polypropylene line. This was not planned for, but the line easily took the weight. The main anchor was soon in the water and the strain on the groundline was lessened. The line on the capstan was constantly monitored for overheating. No overheating was detected at any point in the implanting operation.

The main anchor was lowered by the groundline until it rested on the bottom. The groundline then went slack and the ship was allowed to drift away downwind from the taut line section of the mooring.

The secondary anchor was assembled and shackled to the sling link on the second anchor chain bridle. One leg of the bridle was shackled to the inboard end of the groundline. The other leg was shackled to the outboard end of the 225-foot polypropylene slack line tether. This line was spooled on a reel on the boatdeck. The line was bent around the capstan and a strain was taken on the secondary anchor. The anchor was lifted off the deck and lowered into the water. Once again the full in-water weight of the anchor was sustained by polypropylene line. The line took the weight without visible damage.

The secondary anchor was lowered by the marker float line as the ship continued to drift away from the taut section. The 225-foot polypropylene section was entirely paid out and the weight of the anchor was taken by the 225-foot nylon section. This nylon line had been previously shackled to the polypropylene line. When the anchor was lowered to the bottom, the nylon line went slack. The inboard end of the nylon line was shackled to the 20-foot chain bridle connected to the surface marker float. Finally, the surface marker float was cast overboard.

When the mooring was completely deployed, the main anchor was located at 36°42.2N,121°54.2W. The secondary anchor was located approximately 400 feet due eastward of the main anchor. There was less than a one-half fathom difference in the depths of the sea where the anchors were positioned. The implanting operation was accomplished in less than 45 minutes. The operation went smoothly and efficiently; this was, for a

large part, due to the skill of ACANIA's personnel in handling weights and lines.

An attempt was made to locate the uppermost subsurface buoy on the ship's recording fathometer. The attempts was unsuccessful presumably because of the narrow field of the fathometer and the small target that the buoy presented. The surface marker float appeared to be riding well as the ship set a course for Monterey. ACANIA planned to return to the site several times in the following two weeks to see if the surface marker had been disturbed.

There are few anticipated differences between the procedure for implanting this mooring and the full-scale mooring. The major difference would be the lengths of the lines to be handled. The longer lengths of the full-scale mooring would result in more time required for the total operation. Another difference would be the extra time required to attach the third current meter to the taut line section of the mooring as that section is assembled and put over the side. It was shown that the anchor weights required for the full-scale mooring could be handled with ease.

B. RETRIEVING THE MOORING

1. General Considerations

The small-scale mooring in Monterey Bay was to be on station for only two weeks in a relatively shallow sheltered area.

As explained earlier the full-scale Type II mooring was designed to use the mechanical release as a backup system for recovery; the surface marker line was to be the primary means of recovery. It was decided to reverse this

recovery priority and use the mechanical release as the primary method of recovery for the small mooring for the following reasons:

- The nearness of ACANIA's berth to the mooring site in Monterey Bay lessened the distance that the ship had to travel to recover the mooring. It was felt that there would be a good chance that the ship could arrive at the Monterey Bay site at the preset time of mooring release. If the full-scale mooring were to use the timed release as the primary means of recovery, and if the ship were to arrive after the release had triggered, the current meters and the subsurface buoys would be at the surface of the sea for a period of time. The lengths of buoyant polypropylene line which might be floating at the surface would present a hazard to passing boats and the buoys would be vulnerable to vandalism.
- The relatively sheltered test site for the small-scale mooring lessened the chance that the release of the mooring would occur when sea-state conditions forbade recovery.

Previously used methods to recover U-moorings were not appropriate for moorings fitted with an anchor release since none of the earlier U-moorings had this feature. A new recovery technique had to be devised for the small-scale mooring. Actually there was a simplification in procedure by using the Type II U-mooring design fitted with a mechanical

release. The main anchor would be separated from the mooring and only the secondary anchor would have to be recovered. Separate plans had to be made to recover the mooring in the event that the release would fail to trigger and in the event that grappling would be necessary.

2. Retrieving the Mooring by ACANIA

ACANIA was underway for the mooring site at 0520 on 27 July 1972. It was planned that the ship was to arrive at the site before the time of mooring release. Early arrival would help to determine the accuracy of the mechanical time release by allowing observation of the surfacing of the taut portion of the mooring. The mooring release had been set to actuate at 0600.

At 0610 ACANIA arrived in the vicinity of the mooring site. Visibility was restricted to less than 1000 yards by fog, there was a slight northwesterly swell, and the wind was westerly at five to seven knots. The surface marker was located visually and the ship stood off downwind waiting for the release to occur.

At 0700 it was decided that the release had malfunctioned or had been fouled in the main anchor. Recovery operations commenced when ACANIA was brought alongside and downwind of the surface marker buoy.

As in the implanting procedure, the recovery operation took place portside, amidships, from the main deck extendable platform. After some discussion it was decided to wind the retrieved synthetic line directly onto the hydrographic winch drum, rather than using the capstan and

wooden cable reels. It was felt that this would be a safer approach since the cable would be wet and slippery.

The outboard end of the hydrographic winch wire was shackled to the padeye ring on the top of the marker buoy. The buoy was winched clear of the water and the chain bridle beneath the buoy was manually hauled aboard and stopped off at the swivel under the sling link. The buoy was lowered to the deck and the winch wire was detached. The buoy-chain-sling link assembly was unshackled and put aside. The end of the three-sixteenth inch winch wire was shackled to the inboard end of the nylon section of the slack line. The winch took a strain on the nylon line and the stopper cable was removed. The line was spooled on the hydrographic winch drum as it was recovered. An increase in tension was observed as the secondary anchor was lifted clear of the bottom.

A problem developed when the shackle-swivel-shackle assembly that joined the nylon line to the polypropylene line would not pass freely over the small spooling pulley on the winch. A nylon stopper cable was secured to the polypropylene line outboard of the pulley. This stopper cable was permitted to take the strain of the anchor weight. The hardware assembly then passed easily over the pulley without strain on the cable. The polypropylene line took the weight again and it was winched aboard on the drum until the secondary anchor was out of the water and on deck. A stopper cable was hooked to the thimble on the inboard end of the groundline.

The outboard end of the slack portion of the mooring and the inboard end of the groundline were unshackled from the chain bridle on the secondary anchor. The ship was maneuvered to take some of the strain off the groundline so that the cable could be more easily handled. The line ends were shackled together.

The winch took a strain on the groundline and spooled it on the drum. An increase in tension indicated that the main anchor had lifted clear of the bottom. As the main anchor was raised, the uppermost subsurface buoy broke the surface about 50 yards away from the ship. Shortly afterwards, the lower buoy surfaced very close to the ship. There was some concern that the main anchor would damage the lower current meter if the instrument were to ride up on the anchor. However, by the time that the anchor approached the sea surface the ship had drifted well clear of the buoy-meter combination.

The main anchor was winched on deck and the release was examined. It had not triggered and apparently had not been fouled in the anchor chain. It was set aside for later examination.

The inboard end of the 89-foot polypropylene taut line section was hand-hauled aboard until the lower buoy-meter assembly could be manually lifted aboard. This buoy and meter were then removed. The 127-foot polypropylene line was hand-hauled aboard and the remaining buoy-meter assembly was lifted aboard. The recovery was complete and the ship set a course for Monterey harbor. The entire recovery

operation took less than one hour. During the return trip the line was transferred from the hydrographic winch drum to the wooden cable reels.

All of the components of the mooring were closely examined during and after recovery. The current meters were still operating, as evidenced by the audible sonar pulses every ten minutes. There appeared to be no fish-bite, chafing, or trawling damage on the synthetic line; all splices in the line were still in good condition. The lower polypropylene portion of the slack line was dirty and was thought to have been on the bottom at some time during the two week period. Corrosion appeared to be minimal on all components, with the exception of the non-stainless steel safety wire used on the current meters; this wire had deteriorated completely. Wherever stainless steel wire was used the wire showed no signs of corrosion. All of the shackle pins were still tight and all of the hardware fittings were undamaged. The only evidence of biological activity was a thick clear slime on the synthetic line near the main anchor and a cream-colored three-inch anemone attached to the side of one of the main anchor cans.

Because of the failure of the mechanical time release the recovery procedure that was used was the primary recovery procedure of the Type II full-scale mooring. The main anticipated difference between the full-scale mooring and the small-scale mooring recovery is the lengths of mooring cable to be handled. The longer lengths of cable in the full-scale mooring would necessitate a longer recovery operation.

There would also be one more current meter to remove from the full-scale taut line portion of the mooring.

If the release had functioned, the recovery procedure would be opposite in order of events to that described above. The uppermost subsurface buoy would be recovered first; the last item on deck would be the surface marker buoy. The only anchor that would have to be recovered would be the secondary anchor. The handling of the components would be similar to the surface buoy-first procedure.

The ship was prepared to grapple for the groundline if this means of recovery had been required. The grapple hook would snag the groundline and the groundline would be pulled to the surface with the hydrographic winch. When the bight of the groundline had surfaced on the grapple hook it would be transferred to the hook of a painter cable. The painter cable would be winched in and the doubled-up groundline would be spooled on the winch drum until one of the anchors had surfaced. This anchor would be removed from the groundline; if it were the secondary anchor the slack line and marker buoy (if this buoy had been sunk rather than lost) would then be hauled aboard. If the first anchor recovered were the primary anchor then the subsurface buoys (now at the surface) and the current meters would be hauled aboard. The remaining anchor would then be winched up by the length of groundline still attached to it. Finally, the taut or slack portion of the mooring (depending on which anchor was recovered last) would be hauled aboard.

VI. CONCLUSIONS AND RECOMMENDATIONS

The U-style mooring system can be successfully deployed and retrieved by R/V ACANIA. The performance of the mooring design was adequate for the two week on-station time in the shallow waters of Monterey Bay. The U-style mooring promises to be of value for positioning a current meter array in deeper and more open waters for a longer period of time.

In subsequent deployments of this system certain precautions should be taken. The remote release should be thoroughly bench-checked before the mooring is positioned. For long duration deployments there should be some form of galvanic protection (zinc plates, etc.) on the various steel components of the mooring. A more visible surface marker buoy and a correspondingly stronger slack line and heavier secondary anchor than used in the mooring in the protected waters of Monterey Bay would be prudent for future moorings in deep water.

APPENDIX A

DESCRIPTIONS OF COMPONENTS OF MOORINGS

POLYPROPYLENE LINE

Manufacturer: Tubbs - Great Western Cordage

Diameter: 3/8" (unstretched)

Tensile Strength: 2700 pounds

Working Load: 450 pounds (17 percent tensile strength)

Weight: .028 pounds per foot (air); - .003 pounds per foot (water)

Construction: Standard three-strand twisted construction, gold colored

Elongation Characteristics: See Figure A-1

Splice: Eye spice on steel thimble with at least 8 tucks

NYLON LINE

Manufacturer: Tubbs - Great Western Cordage

Diameter: 3/8" (unstretched)

Tensile Strength: 3700 pounds

Working Load: 410 pounds (11 percent tensile strength)

Weight: .035 pounds per foot (air); .003 pounds per foot (water)

Construction: Standard three-strand twisted construction, white colored

Elongation Characteristics: See Figure A-1

Splice: Eye spice on steel thimble with at least 8 tucks

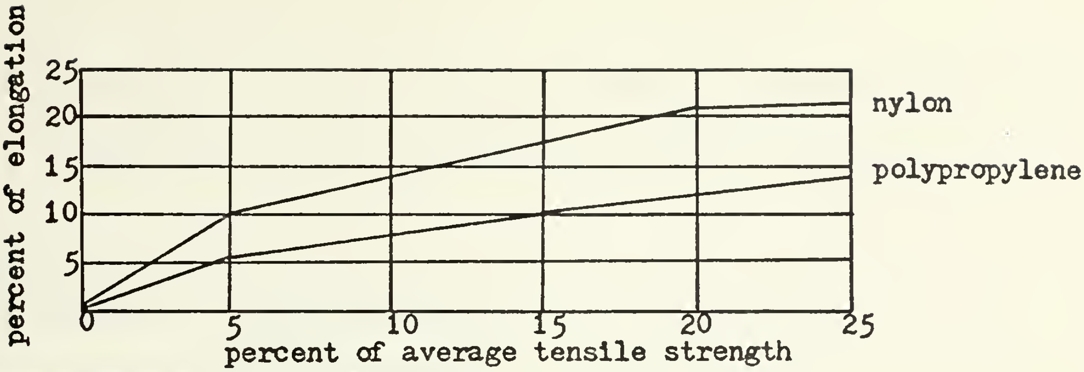

FIGURE A-1 - NYLON AND POLYPROPYLENE LINE HAVE DIFFERENT ELONGATION CHARACTERISTICS.

CHAIN

Manufacturer: Columbus McKinnon Chain Division

Product Name: Inwell Chain, Proof Coil

Trade Size: 5/16"

Working Load Limit: 1750 pounds

Weight: 1.15 pounds per foot (air); 1.00 pounds per foot (water)

Material: Hot galvanized steel

Important Dimensions: Link thickness - 5/16"

Link inside width - 5/8"

SHACKLES

Manufacturer: Crosby-Laughlin

Product Name: Load-Rated

Size: 3/8"

Ultimate Strength: 12,000 pounds

Working Load Limit: 2000 pounds

Weight: .3 pounds (air); .26 pounds (water)

Material: Galvanized forged steel, alloy shackle pins

Important Dimensions: Inside width at pin - 21/32"

at bow - 1-1/32"

pin diameter - 7/16"

Note: Shackle pins were wired in place to prevent them from falling out due to the motion of the mooring.

SWIVELS

Manufacturer: Crosby-Laughlin

Product Name: Regular G-402

Size: 3/8"

Ultimate Strength: 11,250 pounds

Working Load: 2250 pounds

Weight: .68 pounds (air); .59 pounds (water)

Material: Galvanized forged steel

Important Dimensions: Eye diameter - 1-1/4"
Eye thickness - 3/8"

THIMBLES

Manufacturer: Crosby-Laughlin

Product Name: G-411

Size: For 3/8" diameter rope

Weight: .075 pounds (air); .070 pounds (water)

Material: Galvanized Steel

Note: Thimbles were not the "housed" type. The synthetic line was held in place on the thimble by tightly-wound plastic tape.

SLING LINKS

Size: 1/2"

Ultimate Strength: Greater than 20,000 pounds

Weight: .53 pounds (air); .46 pounds (water)

Material: Steel

Important Dimensions: Link thickness - 7/16"

Link diameter - 5"

SUBSURFACE BUOYS

Manufacturer: Manufactured by multiple contractors from plans provided by Naval Postgraduate School

Size: Spherical, 1.94' diameter

Design Maximum Depth: 1000 meters (3280 feet)

Weight: 84 pounds (air); -159 pounds (water)

Material: Cast aluminum

Construction: Two flanged hemispheres with machined O-ring seal, joined together by bolting

CURRENT METERS

Manufacturer: AANDERAA

Product Name: Model 4

Size: See Figure A-2

Tensile Strength of Mooring Spindle: 4410 pounds

Design Maximum Depth: 2000 meters (6550 feet)

Weight: 61.9 pounds (air); 43.4 pounds (water)

Material: Pressure case - 90/10 CuNi alloy, nickle plated

Directional vane - PVC

Drag coefficient: .80

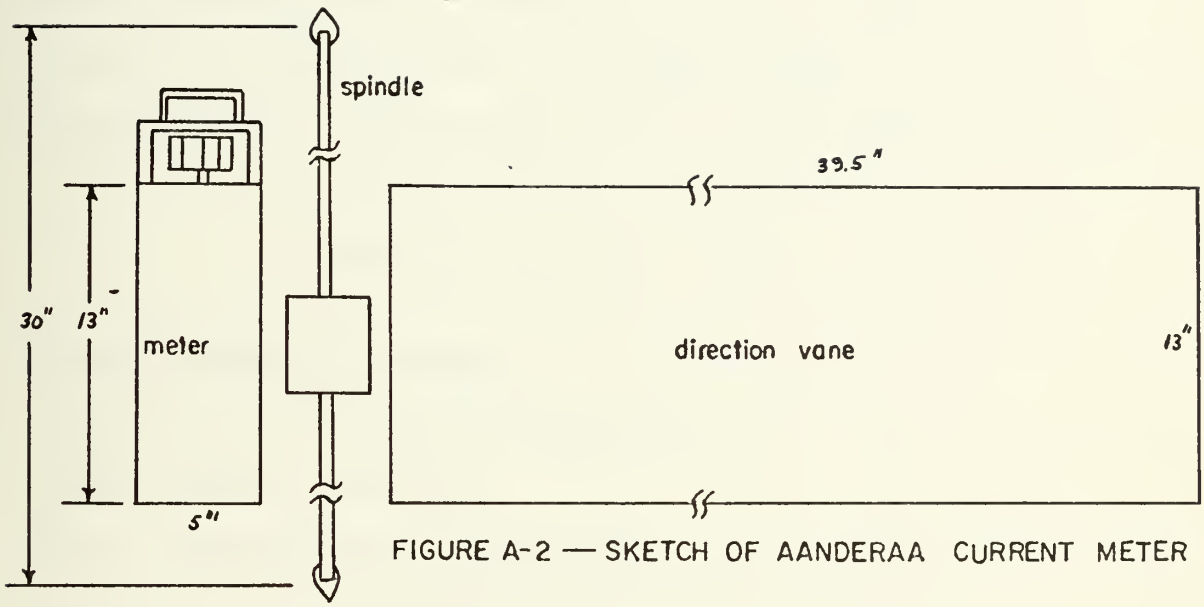

FIGURE A-2 — SKETCH OF AANDERAA CURRENT METER

ACOUSTIC RELEASE

Manufacturer: American Machine and Foundry Company

Product Name: Model 280

Size: Cylindrical - 7.87" diameter

40.25" total length

Release Load Capability: 1000 pounds

Design Maximum Depth: 3000 feet

Weight: 38 pounds (air); 17 pounds (water)

Other Details: Operational range - 2 to 4 nautical miles

Battery life - 6 months

Drag coefficient - .80

TIMED MECHANICAL RELEASE

Manufacturer: Braincon Corporation

Product Name: Type 422

Size: Cylindrical - 9" diameter

13" total length

Release Load Capability: 8000 pounds

Design Maximum Depth: 5000 meters (16,400 feet)

Weight: 38 pounds (air); 17 pounds (water)

Other Details: Maximum time duration - 400 days (one hour increments)

Drag coefficient - .80

ANCHOR (250 POUND MAIN ANCHOR)

Composition: Two concrete-filled cans (rectangular - 16"X 16"X11") joined together by 5/16" chain and shackles (Figure A-3)

Weight: Each can - 230 pounds (air), 125 pounds (water)

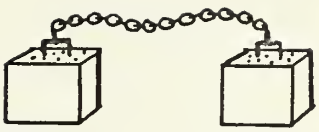

FIGURE A-3 - THE MAIN ANCHOR IS CONSTRUCTED BY CHAINING TOGETHER TWO RECTANGULAR CONCRETE-FILLED CANS.

ANCHOR (230 POUND SECONDARY) - For Type I Mooring

Composition: Four concrete-filled cans (cylindrical - 11" diameter, 13.5" length) joined together by 5/16" chain and shackles (Figure A-4)

Weight: Each can - 104 pounds (air), 57 pounds (water)

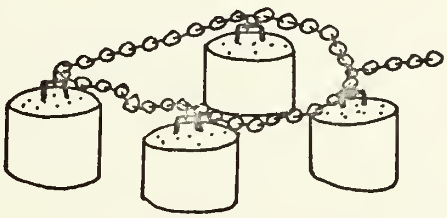

FIGURE A-4 - THE SECONDARY ANCHOR IS CONSTRUCTED BY CHAINING TOGETHER SEVERAL CYLINDRICAL CONCRETE-FILLED CANS.

ANCHOR (285 POUND SECONDARY) - For Type II Mooring

Composition: Five concrete-filled cans (cylindrical - as above) joined together by 5/16" chain and shackles. Similar in construction to the 230-pound secondary anchor.

SURFACE MARKER BUOY

For the small-scale mooring a spherical, 4.5 foot diameter, hollow Mk. 6 mine casing was used. The casing weighed approximately 150 pounds and was painted a bright orange.

For the full-scale mooring a larger marker buoy should be used since the mooring would be positioned in or near a

region where coastal sea traffic might be expected to be present. Additionally, a strobe marker light should be installed and the location of the buoy should be reported to the Coast Guard well before the actual implanting takes place. This prior notification would enable the Coast Guard to produce a Notice to Mariners which would publicize the location of the mooring. The larger buoy can be selected from the various ones that the Naval Postgraduate School owns; however, if the buoy is very much larger than the one used for the small-scale mooring the slack marker line should be correspondingly larger in diameter and the secondary anchor must be heavier.

APPENDIX B

COMPUTER ANALYSIS

Computer programs were written and run on the Naval Postgraduate School's IBM 360 Computer to determine the physical profile and the forces acting on the taut portion of the mooring to be deployed in 1800 feet of water. There were two basic programs written: one that investigated the effects of placing subsurface buoys at various locations on the mooring, and another that helped select the cable lengths used in the mooring. The second program was a specialized adaptation of the first. In both programs the static profile of the taut portion of the mooring under the influence of a current profile was calculated. This profile was then drawn out by a CALCOMP plotter. Additional information such as angles and tensions in the mooring cable and resultant forces on the main anchor were computed. Line stretch was considered whenever necessary; this factor is very important when synthetic line is used in a mooring system.

A. GENERAL CONSIDERATIONS

The following mathmetical approach was used as a basic tool in the programs. The basic equations were published as part of an analysis of a moored mine [McMahon, 1956] and were used [Ostericher, 1967] to calculate the dip and excursion of a taut moored subsurface buoy. In this thesis these equations are adapted to computer use.

Consider a segment or section of mooring cable (Figure B-1). The only forces acting on the cable are gravity, buoyancy, and current.

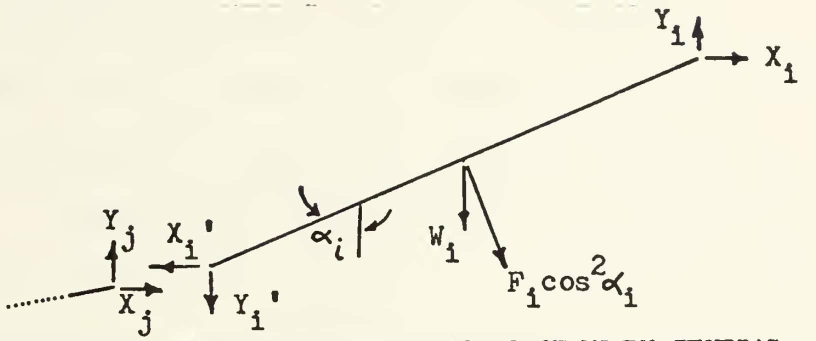

FIGURE B-1 - EACH CABLE SECTION IS ACTED UPON BY SEVERAL FORCES.

In Figure B-1, F_i is the force per unit length due to drag when the cable section is normal to the flow.

W_i is the cable section weight.

α_i is the angle between the cable section and the vertical.

Y_i and X_i are the vertical and horizontal components of cable tension.

Summing the horizontal and vertical forces on the cable section and taking moments of the forces on the cable section about the midpoint:

1. $X_i' = X_i + F_i \cos^3\alpha_i$

2. $Y_i' = Y_i - W_i - F_i \cos^2\alpha_i \sin\alpha_i$

3. $\tan\alpha_i = \dfrac{2X_i + F_i \cos\alpha_i}{2Y_i - W_i}$

The configuration of the taut portion of the mooring was determined by solving for the forces in each successive cable section. Equilibrium requires that X_i' equal X_j and

that Y_i' equal Y_j. Equations 1, 2, and 3 above were well suited for computer use. DO loops could be readily used to calculate the angles from the vertical of each section and the X and Y components of tension at the top and bottom of successive sections.

The appearance of the cosine term on the right side of equation 3 presented a problem by making the equation transcendental. In the first computer program this cosine term was assumed to be equal to one. It was felt that this was not a bad assumption, even for relatively large angles (20°-30°), since X_i and Y_i are tension components (large values) in the cable and F_i is a drag force for a cable section. Drag forces for cable sections were considered to be very small since the lengths of cable chosen for the analysis were short (33 feet was the maximum length considered). Hence, the cosine term had little effect on the value of $\tan\alpha_i$.

Whenever $\tan\alpha_i$ was calculated in the second program an iteration was performed. The cosine term was initially chosen to be equal to one. $\mathrm{Tan}\alpha_i$ was then calculated and α_i (from taking the inverse of $\tan\alpha_i$) was substituted into the right side of equation 3. Another $\tan\alpha_i$ was then calculated, using the previously obtained value of α_i. The process repeated once again to obtain a final corrected value of α_i which was used in subsequent calculations.

The drag terms used in the equations were calculated in the following manner. First, a current speed profile was selected. The profile used in the first computer program

is shown in Figure B-2. This profile is similar to a current profile used by Scripps [Isaacs, et al, 1963].

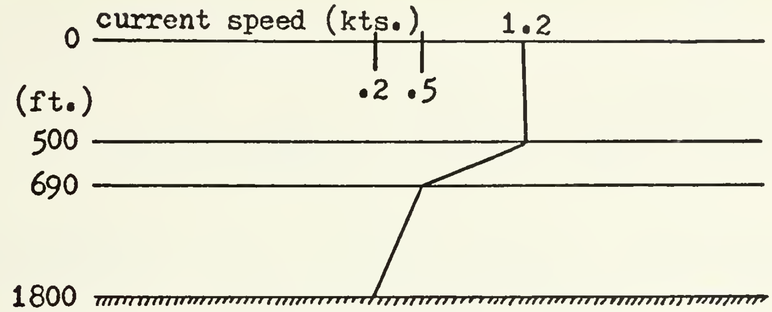

FIGURE B-2 - THE ARRAY IS SUBJECTED TO A SIMPLIFIED CURRENT PROFILE.

In the second program the profile shown in Figure B-2 was used initially. Then profiles of 80, 40, 20, 10, and 5 percent of the current speeds were used to investigate how the mooring behaved under lower current speed profiles.

The drag on each section was calculated with the line section normal to the flow, using the equation:

$$F_i = C_D \frac{\rho}{2} A_i U^2$$

In this equation: ρ is the density of seawater (approximately 2 slugs/ft^3),

A_i is the projected area of the line section, its diameter times its length,

U is the speed of the current,

and C_D is the drag coefficient (1.20 for all line)

U, where not constant with depth, was calculated in two ways. In the first program a simple average of the U value at the top and the bottom of each individual line section was taken. This average value was used in the drag equation.

In the second program an equivalent current speed was calculated for each individual line section along the cable length, where:

$$C_D \frac{\rho}{2} A U_{eq}^2 = \int_0^{\ell} C_D \frac{\rho}{2} U(z)^2 d' dz$$

In this equation: ℓ is the individual line section length,

d' is the line diameter,

dz is an elemental line length,

$U(z)$ is the current speed as a function of depth,

C_D, ρ, and A are as previously defined,

and U_{eq} is an equivalent speed.

The limits of the integration are the beginning and end of each individual line section.

If U_1 is the current speed at the top of the line section and U_2 is the current speed at the bottom of that section, and if the current speed profile is linear with depth, then:

$$U(z) = U_1 - \left(\frac{U_1 - U_2}{\ell}\right) z$$

where z is measured along the line section.

Substituting:

$$C_D A U_{eq}^2 = C_D \int_0^{\ell} \left(U_1 - \left(\frac{U_1 - U_2}{\ell}\right) z\right)^2 d' dz$$

After integration and simplification:

$$C_D A U_{eq}^2 = \frac{C_D d' \ell}{3} \left(U_1^2 + U_1 U_2 + U_2^2\right)$$

But: $A = d'\ell$

Therefore: $U_{eq}^2 = \frac{1}{3}\left(U_1^2 + U_1U_2 + U_2^2\right)$

Or: $U_{eq} = \left(\frac{1}{3}\left(U_1^2 + U_1U_2 + U_2^2\right)\right)^{1/2}$

This is the equation used to calculate the current speeds which were used in determining the drag values in the second program.

Program descriptions in the following discussion are referenced by statement numbers, array names, and other aides which the reader may find useful as he examines the programs.

B. COMPUTER PROGRAM FOR INVESTIGATION OF BUOY POSITIONING ON TAUT PORTION OF THE MOORING

The mooring was initially considered to be in place in the sea with the unstretched line positioning meter 1 at 160 feet below the surface, meter 2 at 640 feet, and meter 3 at 1140 feet (Figure B-3). The mooring cable was divided into line sections of 20 foot-lengths between meters 1 and 2, 25 foot-lengths between meters 2 and 3, and 33 foot-lengths between meter 3 and the anchor. It was felt that the shorter line sections could more accurately approximate the actual shape of the cable where the current was swift or varied relatively rapidly with depth (in the upper part of the mooring).

Line stations are those points on the mooring cable that represent the ends of line sections. For instance, stations 1 and 2 are those points at the top and bottom respectively

of line section 1; line section 24 is contained between stations 24 and 25.

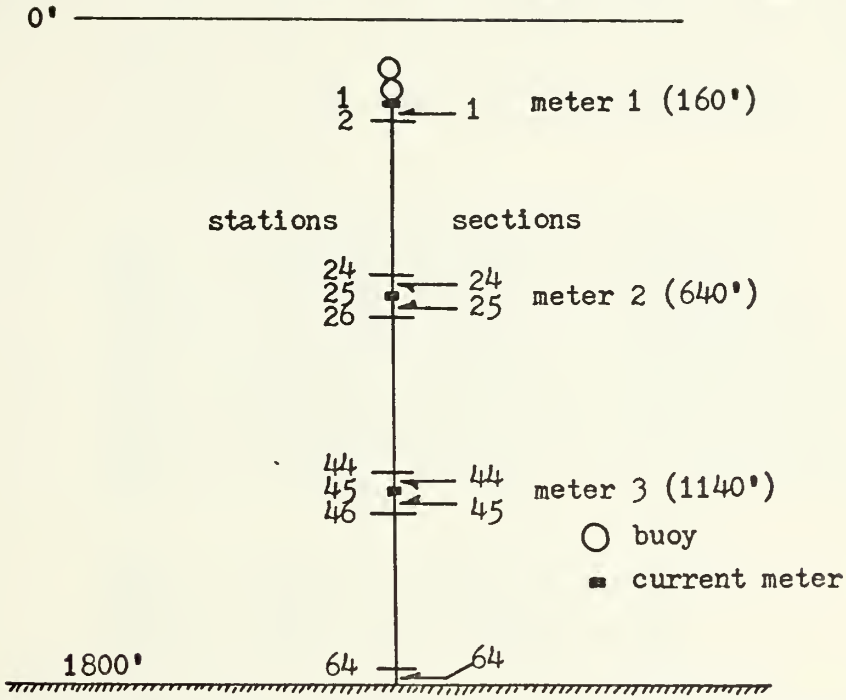

FIGURE B-3 - THE ARRAY IS CONSIDERED IN PLACE IN THE SEA WITH AN INITIAL CONFIGURATION.

Z(I) represents the depth of each station in feet below sea level for the unstretched no-current situation. VV(I) represents the value of the current speed in ft/sec at each station, assuming the current profile to be that illustrated in Figure B-2.

V(J)... The average value of the current speed acting on each line section was calculated by averaging the current speed at the top and bottom of the line section.

READ... The in-water weights of all the components of the mooring were entered into the computer from data cards; likewise, the areas (in ft^2 and ft^2/ft for line) for the larger components were entered (the areas being those presented

to the current if the mooring were vertical). The drag coefficients for the larger components were also entered. Below are the read-in computer constants and their definitions:

WSH - In-water weight of 1 shackle
WSV - In-water weight of 1 swivel
WSL - In-water weight of 1 sling link
WTH - In-water weight of 1 thimble
WCH - In-water weight of 1 foot of chain
WAR - In-water weight of 1 acoustic release
WBU - In-water weight of 1 subsurface buoy
WLN - In-water weight of 1 foot of line
WMR - In-water weight of 1 current meter

ABU - Area of 1 subsurface buoy
ALN - Area of 1 foot of line
AMR - Area of 1 current meter
AAR - Area of 1 acoustic release

CDB - Drag coefficient of subsurface buoy (.50)
CDM - Drag coefficient of current meter (.80)
CDL - Drag coefficient of line (1.20)
CDR - Drag coefficient of release (.80)

D, DM1... The drag on components above station 1 was calculated for two buoys and one meter.

F(1)... The drag on line section 1 (when normal to the flow) was calculated.

Y(1)... The "lift" on station 1 was calculated (i.e. the weights of the meter, shackles, etc., were subtracted from the total lift of the two buoys). This was the total vertical force at station 1.

X(1)... The total horizontal (drag) force at station 1 was determined.

W(1)... The weight of line section 1 was calculated.

Now the following approach was used, utilizing the basic equations previously discussed (Figure B-4).

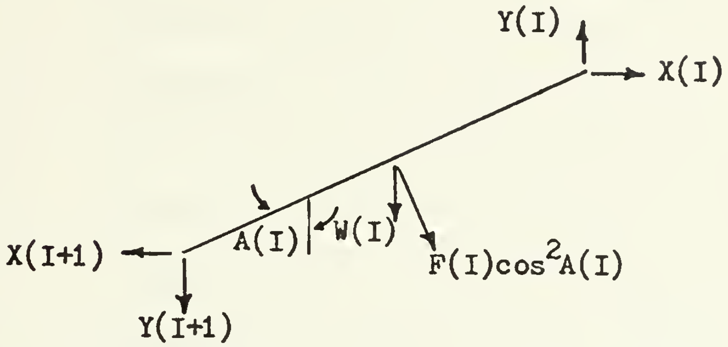

FIGURE B-4 - CABLE SECTION ANGLE AND FORCES ARE EXPRESSED IN COMPUTER NOTATION.

$$X(I+1) = X(I) + F(I)\cos^3 A(I)$$

$$Y(I+1) = Y(I) - W(I) - F(I)\cos^2 A(I)\sin A(I)$$

$$\tan A(I) = \frac{2X(I) + F(I)\cos A(I)}{2Y(I) - W(I)}$$

assuming that:

$$\cos A(I) \approx 1$$

implies:

$$A(I) = \arctan \frac{2X(I) + F(I)}{2Y(I) - W(I)}$$

X(2)... Y(2)... The tension components at the top of section 2 were found from the equations above by using X(1), Y(1), A(1), F(1), and W(1) values.

DO 2000... Sections 2 to 24: The computer calculated F(I), W(I), and A(I) for each section and then calculated X(I+1), Y(I+1) for each section. Next, XAV(I) and YAV(I) were calculated by averaging section tension pairs at the top and bottom of each section. $TAV(I) = (XAV^2 + YAV^2)^{1/2}$ is the average resultant tension in each section. Tension components at station 25 were corrected to

account for the drag and weight additions of meter 2 and its hardware. New values of tension components at station 25 were designated by X(25) and Y(25).

DO 2010...	Sections 25 to 44 were analyzed in the same fashion as that of sections 2 to 24. Tension components at station 45 were corrected to account for the drag and weight additions of meter 3, the acoustic release, and their hardware. New values of tension components at station 45 were denoted X(45) and Y(45).
DO 2020...	Sections 45 to 64 were analyzed in the same fashion as sections 2 to 24 were above.
Y(65)...	Vertical tension at station 65 (the bottom-most station) was corrected to account for the 10 feet of chain and chain hardware above it.
ANCHX, ANCHY	The tension components at the bottom of section 64 are the components of force on the anchor. TANCH represents the resultant force on the anchor.
S(J)...	These are the original unstretched lengths of line (20', 25', and 33').
E(I)...	This equation was derived from the manufacturer's plot of elasticity (elongation versus tension) of the polypropylene line. It was obtained from the linear relationship represented in Figure A-1 for loadings between

5 and 20 percent of average tensile strength. This led to the stretched lengths of line (SS) given by the formula:

$$SS(I) = S(I) + S(I)E(I)$$

3000... Two arrays were formed giving the height, YY(I), and the horizontal displacement, XX(I), of the stations by using the values of A(I) and SS(I) for each section. Calculations were started from the bottom of the mooring, XX(1) and YY(1), and worked upwards to XX(65) and YY(65). Each line section contributed the horizontal and vertical displacements of its uppermost limit to the line section beneath it (Figure B-5).

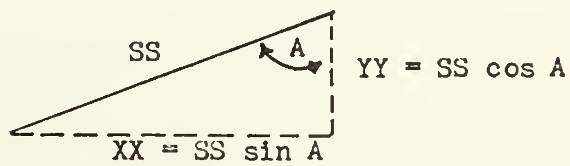

FIGURE B-5 - CABLE SECTIONS FORM MOORING CONFIGURATION USING THEIR STRETCHED LENGTHS AND ANGLES OF INCLINATION.

XM, YM... The XX and YY station locations of the meters (where old stations 1, 25, and 45 were located in terms of XX and YY coordinates) were represented.

CALL DRAW... a. The current speed profile, VV versus Z, was plotted.

b. The mooring configuration was plotted in XX and YY coordinates.

c. The locations of the meters on the mooring configuration were marked with triangles.

The following data was printed out for each line section: average current speed V(I), angle A(I) (converted into degree measure), unstretched length S(I), stretched length SS(I), and average tension TAV(I).

The following data was printed out for each current meter: depth (for no-stretch, no-drag conditions), depth after current acts and line stretches, and horizontal displacement from a point directly above the anchor. Lastly, the resultant force on the anchor was printed out.

The program described above was for the mooring in the configuration shown in Figure B-6, known as MOD 0. This is the mooring whose sample program appears immediately following this Appendix.

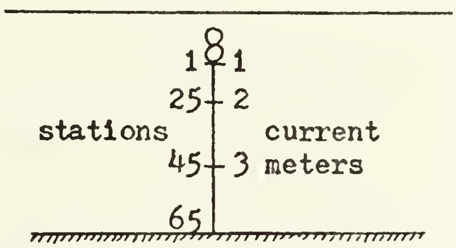

FIGURE B-6 - MOD 0 CONFIGURATION

The effect of different buoy arrangements on the taut line was examined. Certain cards were added to (or removed from) the MOD 0 program deck to model the effect of adding or removing buoys and hardware at certain stations.

MOD 1 - This configuration is like MOD 0, except appropriate corrections to drag and weight at station 1 were made to model the configuration shown in Figure B-7.

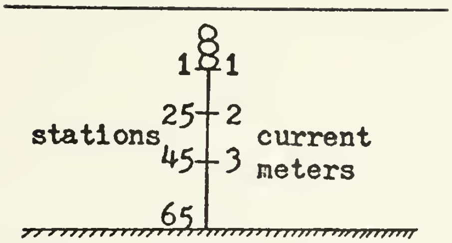

FIGURE B-7 - MOD 1 CONFIGURATION

MOD 2 - As MOD 1, but with corrections to stations 1 and 25 to model the configuration shown in Figure B-8.

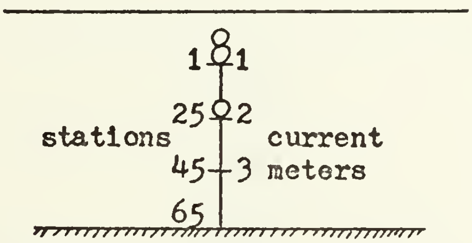

FIGURE B-8 - MOD 2 CONFIGURATION

MOD 3 - As MOD 2, but with corrections to station 1 to model the configuration shown in Figure B-9.

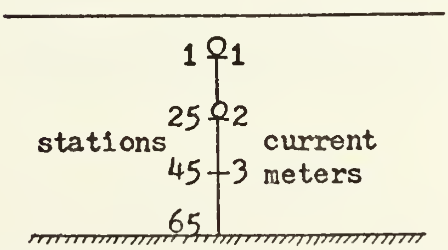

FIGURE B-9 - MOD 3 CONFIGURATION

MOD 4 - As MOD 3, but with corrections to station 45 to model the configuration shown in Figure B-10.

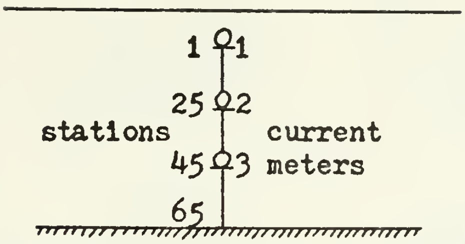

FIGURE B-10 - MOD 4 CONFIGURATION

MOD 5 - As MOD 4, but with corrections to stations 25 and 45 to model the configuration shown in Figure B-11.

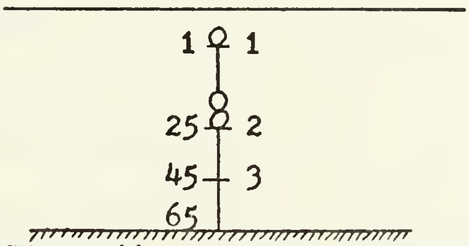

FIGURE B-11 - MOD 5 CONFIGURATION

All of the above models were acted upon by the same current profile and all had the same line stretch characteristics. Table B-I tabulates some results taken from the computer output.

TABLE B-I - INFORMATION FROM COMPUTER MODELS

MODEL	LARGEST LINE TENSION/ SECTIONS	LARGEST ANGLE IN MOORING/ SECTION	LARGEST ANGLE ON METER/ METER	FORCE ON ANCHOR
MOD 0	270#/1-24	31°/64	22°/3	169#
MOD 1	425#/1-24	18°/64	14°/3	318#
MOD 2	382#/25-44	17°/64	13.5°/3	317#
MOD 3	221#/35-44	28°/64	19.5°/3	160#
MOD 4	315#/45-64	32.5°/24	17°/2	309#
MOD 5	375#/25-44	32.5°/24	12°/3	311#

With the above information a choice could be made of the mooring buoy configuration to be used. It was apparent that the MOD 1, MOD 2, MOD 4, and MOD 5 configurations (all three-buoy moorings) had their largest cable tensions much closer to the manufacturer's recommended safe working load for polypropylene line (450 pounds) than the two-buoy moorings. However, the three-buoy moorings imposed smaller angles on the meters when compared to the two-buoy moorings. The three-buoy systems also required much larger anchors than the two-buoy systems. A larger anchor meant more difficulty in implanting operations. Other considerations in the choice of mooring configuration were: ease of implanting and retrieval (two-buoy moorings superior), redundancy in the event of buoy failure (three-buoy moorings superior), and availability of proven buoys at the Naval Postgraduate School (two or three-buoy systems could be built).

The current speed profile specified was a conservative profile for the area under consideration because it modeled a fairly strong current and was unidirectional. Any other

current profile likely to be encountered would probably lead to lesser angles and lesser tensions in the mooring.

The configuration chosen was MOD 3 - a two-buoy mooring requiring a small anchor and subjecting the current meters to reasonable angles of tilt. With the MOD 3 buoy configuration system chosen the task of actually designing the system was still ahead, and towards this end the second computer program was written.

C. NOTES ON THE "REEL" COMPUTER PROGRAM

The second program was similar to the first but was written to adjust the lengths of the unstretched line sections. Lengths were determined to put the top meter within a specified number of feet of the 160-foot depth mark when the mooring is acted upon by the current profile. There were also sophistications in the manner of specifying the current profile and in calculating drag on the line sections. Additionally, the effect of reducing the current was examined.

This program was designated as the REEL program since it "reels" out cable from each line section to place the top meter where desired. The REEL program used the MOD 3 buoy configuration selected in the previous analysis.

The program is discussed by referencing certain parts of the program by key statement numbers, etc. REEL program is illustrated following the illustration of the program discussed in Section B.

A brief explanation follows of what is being done by the computer as it executes the REEL program:

1. Velocity profile with depth is calculated.

2. Depth of each station is calculated for the mooring in the no-current, no-stretch condition (Figure B-12).

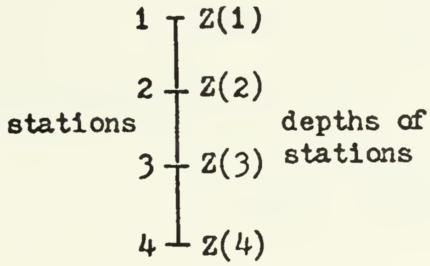

FIGURE B-12 - Z(I) REPRESENTS THE DEPTH OF STATION I.

3. Equivalent current speed acting on each section is calculated, as previously discussed.

4. Current acts on sections. Sections are considered separately, and there is continuity in tension from the bottom of one section to the top of the next. Corrections are made for any concentrated weights or buoys on the mooring. Sections incline (Figure B-13).

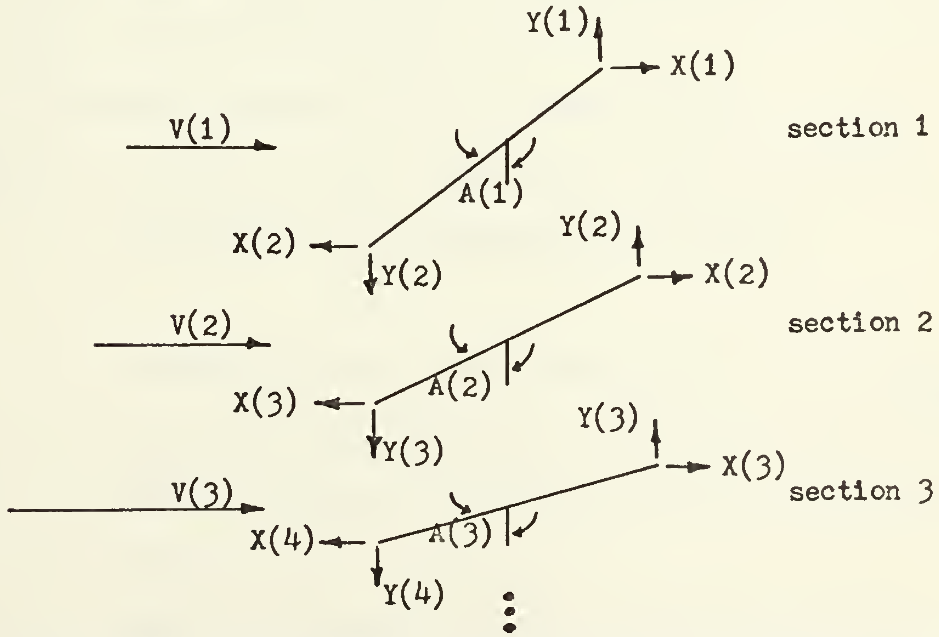

FIGURE B-13 - THE CURRENT ACTS ON SECTIONS AND THERE IS TENSION CONTINUITY FROM ONE SECTION TO THE NEXT.

5. Stretch is computed by elongation formula using the average of tensions at the top and bottom of each line section.

6. Sections are "joined" together mathematically for purposes of plotting (Figure B-14).

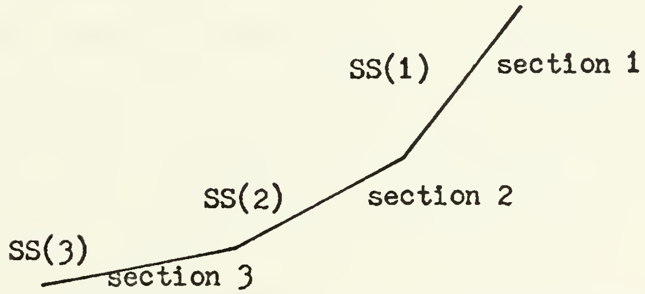

FIGURE B-14 - SECTIONS ARE JOINED TOGETHER MATHEMATICALLY TO FORM THE MOORING CONFIGURATION.

7. If top meter is not where it should be, the computer goes to step 2 and extends unstretched line sections by one percent and recomputes steps 3 to 7.

8. Computer now goes to step 3 with a smaller current profile and with the final unstretched line lengths frozen into the program.

A more detailed treatment of the REEL program follows:

C COMPONENTS... Weights, areas, and drag coefficients were entered in the computer, as before.

VV(I):

DO 1030... Current values were determined for each foot depth from zero to 500 feet below sea level.

DO 1040... Same as above, for 500 to 690 feet below sea level.

DO 1050... Same as above, for 690 to 1800 feet below sea level.

The above three DO loops used the current speed profile that is shown in Figure B-2.

DO 5000... This loop enabled a return to the DO 3035 loop after the length of the mooring had been adjusted. Mooring was subjected to current profiles of 80, 40, 20, 10 and 5 percent of the original profile.

DO 3035... This loop incremented ("reeled") the length of each line section by one percent, from zero to a maximum of 12 percent, in an effort to get the top meter within a certain distance of the 160-foot depth mark. The target value that was chosen for this program was 30 feet.

P = ... P is the fractional increment used to adjust the line section lengths by one percent.

DO 1025... This loop obtained the values of current, VD(I), for each 25-foot depth mark, ZD(I), for current profile plotting on the CALCOMP Plotter.

Z(I):

DO 1000... The depth of each station from 1 to 25 was calculated after line section lengths had been incremented. Section lengths were 20' initially.

DO 1010... Same as above for stations 26 to 45. Section lengths were 25' initially.

DO 1020... Same as above for sections 46 to 65. Section lengths were 33' initially.

DO 1060... Each value of Z(I) obtained in the last three DO loops was rounded off to integer form.

V(J):

DO 1062...,
DO 1063...,
DO 1064... Equivalent current speeds for each section were calculated for drag calculations to follow.

The following work was performed by the computer, similar to that done in the previous program:

a. Drag on upper two buoys was calculated and then corrected to MOD 3 configuration.

b. Drag on meter 1 was calculated.

c. Drag on line section 1 was calculated.

d. Vertical component of tension at top of line section 1 was calculated and corrected for MOD 3 configuration.

e. Horizontal component of tension at top of line section 1 was calculated.

f. Weight of line section 1 was calculated (the incremented length weight).

g. Angle of section 1 was calculated.

h. As in the previous computer program, the computer calculated angles and tension components, making appropriate corrections demanded by meters and buoys and using the MOD 3 configuration. Line increments were considered whenever necessary.

i. Anchor tension was computed.

DO 2050... Average tension in each line section was computed.

DO 2060...,
DO 2070...,
DO 2080... Unstretched incremented lengths of sections were calculated.

DO 3000... Stretched section lengths were calculated, using elastic properties of polypropylene line, as in the previous program.

The mooring line stations were arranged for plotting as in the previous program.

IF(ZM1.LE... This enabled a jump out of DO loop 3035 if the top meter came within 30 feet of the 160-foot depth mark. When the jump-out occured, a plot was made of the current profile and the physical configuration of the mooring. MM stored for later use the last K value used. Mooring parameters were printed out as before.

3049... B, C, and G, are CALCOMP Plotter scale constants.

4085, 4087,
4089, 4092, and
4094 The VV(I) values were determined for a new current profile for use in another run through the DO 5000 loop.

The resulting printout illustrated the physical shape of the mooring under current speed profiles of 100, 80, 40, 20, 10, and 5 percent of the original profile and presented complete information (angles, tensions, anchor data, etc) for each case.

D. CONCLUSIONS DRAWN FROM REEL PROGRAM

The work with the computer indicated that each unstretched line section had to be extended one percent. This would put the top current meter within 30 feet of the 160-foot depth under the strongest current profile considered. This meant that sections 1 to 24 had to be 20.20 feet long, sections 25 to 44 had to be 25.25 feet long, and sections 45 to 64 had to be 33.33 feet long. These were all unstretched line lengths. The length of the mooring line between the first and second meter had to be (20.20)(24) = 485 feet; that line between the second and third meter had to be (25.25)(20) = 505 feet; and that line between the third meter and the anchor had to be (33.33)(20) = 666 feet long. These were the lengths of cable that could be measured on shore and precut for the mooring. Table B-II shows additional information obtained from the REEL program.

TABLE B-II - INFORMATION FROM THE REEL PROGRAM

CURRENT PROFILE (PERCENT OF MAXIMUM PROFILE)	DEPTHS (IN FEET BELOW SEA LEVEL) METER 1	METER 2	METER 3
100	189	663	1175
80	107	601	1130
40	40	551	1093
20	36	548	1090
10	35	548	1090
5	35	547	1090
Current meter array design:	160	640	1140

It should be noted that, as the current slackened to a speed close to zero, the top meter asymptotically approached 35 feet in depth; likewise, the other meters approached asymptotic depth limits.

However, it must be remembered that this was a very artificial analysis which was extremely dependent upon assumptions of unidirectional current, uniform and accurate line elongation information, and artificial current profiles, among other things. At best, this analysis indicated that there would be very considerable excursions of the meters as the current profile changed. It was seen that the meters could be expected to be "reasonably" close to the array design depths for a current profile between 100 and 80 percent of the maximum profile examined. For lesser profiles the meters would rise up through the water and approach limiting depths as the current speed went to zero. Perhaps, when data is recovered from this current meter array, a more realistic current profile can be determined and entered into the REEL program to enable a more accurate physical picture of the array to be computed.

It should be noted that the computer analysis was performed for the taut line portion of the mooring in the Type I configuration (with an acoustic release). As discussed earlier, there was a difference between Type I and Type II as to where the release was placed on the mooring. However, the in-water weights of the acoustic and mechanical releases (15 and 17 pounds, respectively) and their drag areas (1.42 and .80 ft^2, respectively) were small enough such that it

could be assumed that the array would present about the same configuration for both Types under the influence of current. In fact, if the Type II system were used (with the release just above the anchor) the total drag on the mooring would be less because the release would be in a lower current speed compared with the Type I release position. There would be less dip of the meters from their no-current positions, and this could help to keep the meters at their design depths.

Figures B-15a and B-15b are illustrations taken from the computer plot for 100% and 40% current speed profiles.

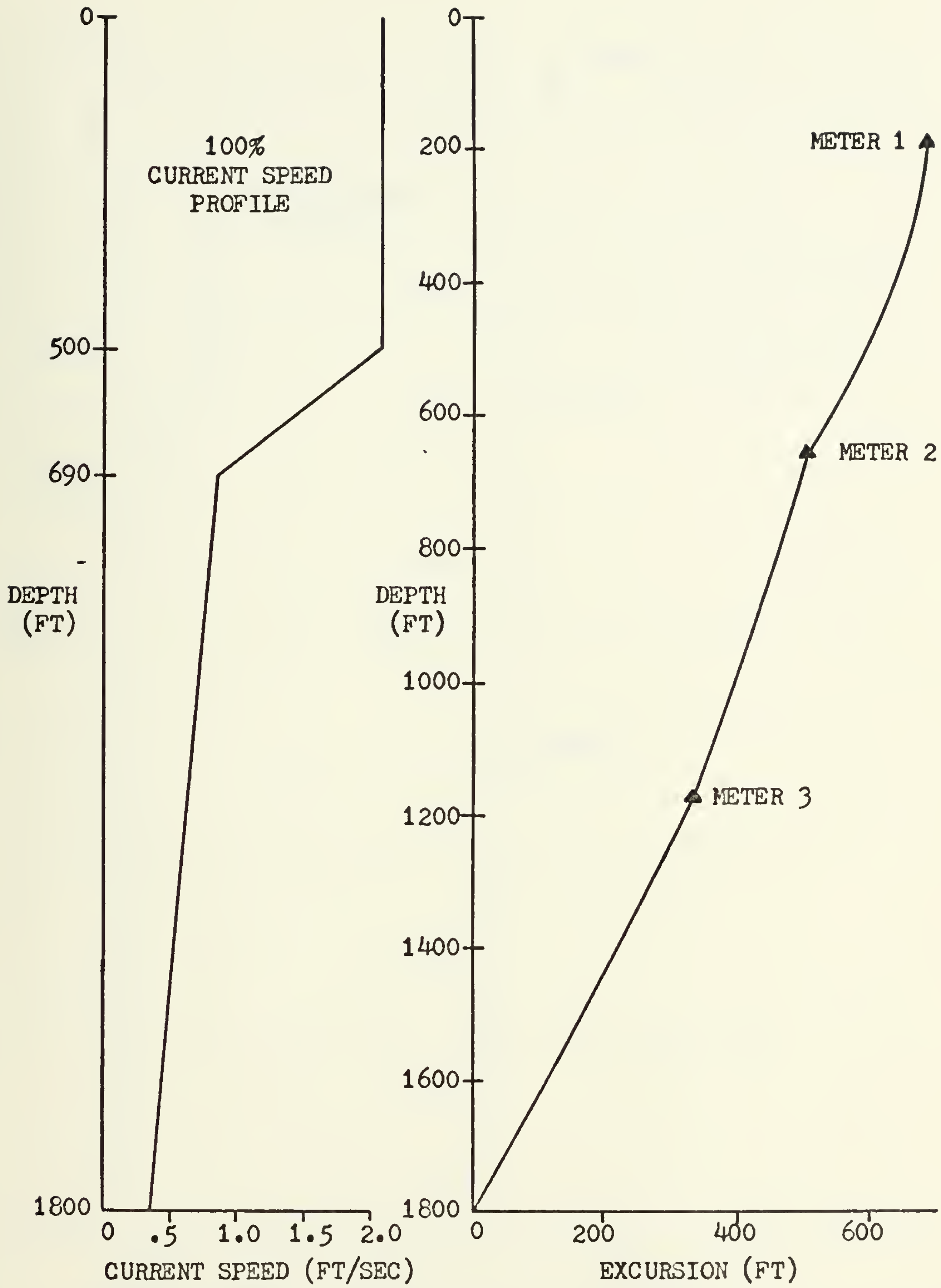

FIGURE B-15a - THE CURRENT METER ARRAY ASSUMES THE ILLUSTRATED CONFIGURATION UNDER THE INFLUENCE OF A 100% CURRENT SPEED PROFILE.

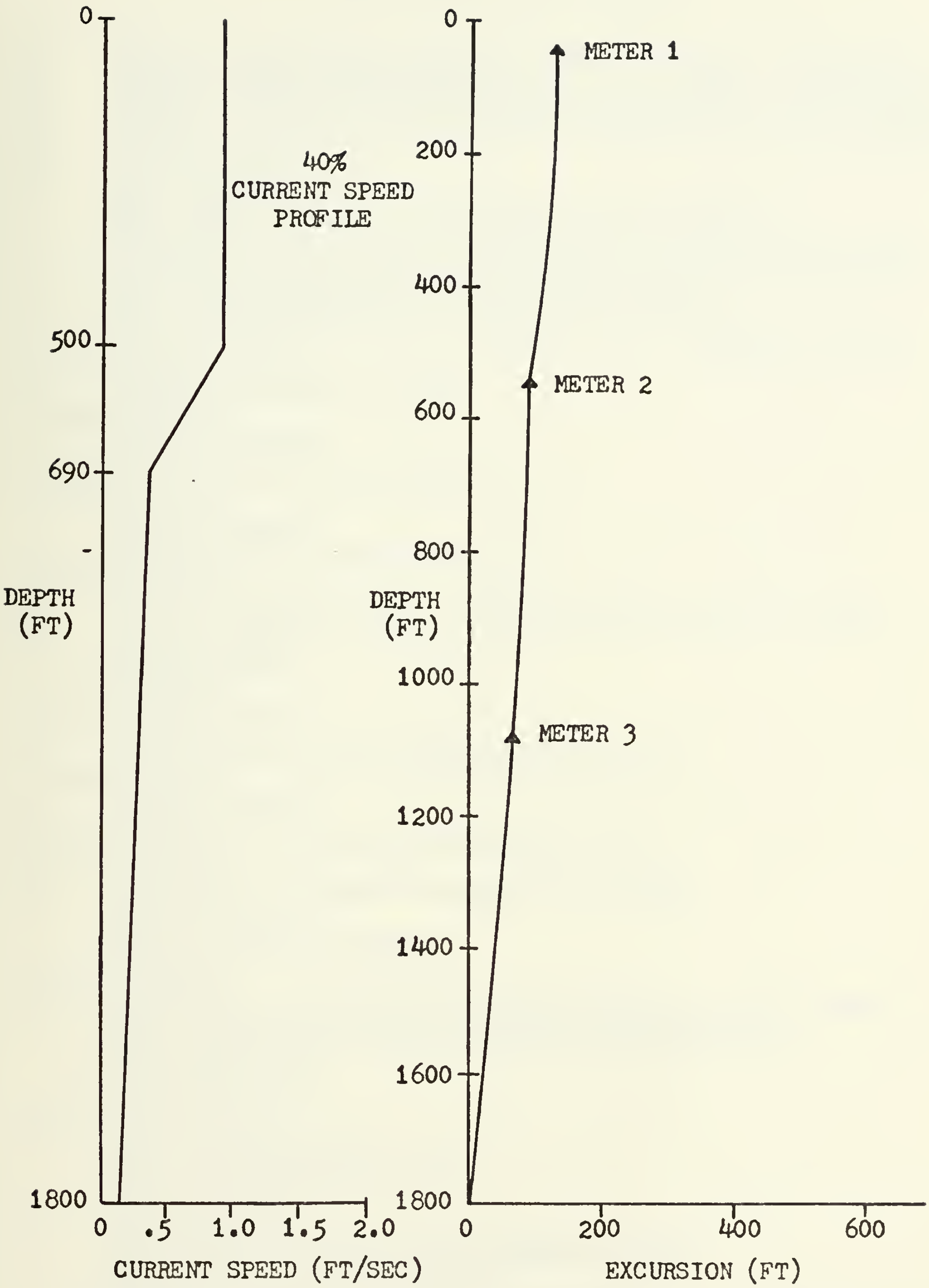

FIGURE B-15b - THE CURRENT METER ARRAY ASSUMES THE ILLUSTRATED CONFIGURATION UNDER THE INFLUENCE OF A 40% CURRENT SPEED PROFILE.

BUOY POSITIONING PROGRAM

```
C     PROGRAM TO COMPUTE APPROXIMATE CONFIGURATION OF SUBSURFACE MOORED
C     CURRENT METER ARRAY UNDER INFLUENCE OF CURRENT. PROGRAM WILL
C     PRODUCE A PLOT OF THE MOORING CONFIGURATION, A PLOT OF THE ASSUMED
C     CURRENT PROFILE, AND WILL COMPUTE VARIOUS IMPORTANT PARAMETERS
C     OF THE ARRAY.
      REAL*8 ITITLE(12)
      REAL LABEL1/'VELO'/,LABEL2/'MOOR'/,LABEL3/'METR'/
      DIMENSION Z(65),VV(65),V(64),F(64),Y(65),X(65),W(64),A(64),
     1XAV(64),YAV(64),TAV(64),S(64),SS(64),E(64),YY(64),XX(64),
     2YC(64),XC(64),XM(3),YM(3),ZA(3),ZB(3),AA(64)
C     DEPTH OF EACH STATION IS COMPUTED FOR NO STRETCH, NO DRAG
      DO 1000 I=1,25
      Z(I)=20.0*FLOAT(I-1)+160.0
 1000 CONTINUE
      DO 1010 I=26,45
      Z(I)=25.0*FLOAT(I-25)+640.0
 1010 CONTINUE
      DO 1020 I=46,65
      Z(I)=33.0*FLOAT(I-45)+1140.0
 1020 CONTINUE
C     VALUE OF ASSUMED CURRENT PROFILE FOR EACH Z(I) IN FT/SEC
      DO 1030 I=1,18
      VV(I)=1.2*1.69
 1030 CONTINUE
      DO 1040 I=19,27
      VV(I)=(1.2-(.7/190.0)*(Z(I)-500.0))*1.69
 1040 CONTINUE
      DO 1050 I=28,65
      VV(I)=(.5-(.3/1110.0)*(Z(I)-690.0))*1.69
 1050 CONTINUE
C     AVG VALUE OF CURRENT FOR EACH LINE SECTION
      DO 1060 J=1,64
      V(J)=(VV(J)+VV(J+1))/2.0
 1060 CONTINUE
C     COMPONENTS IN-WATER WEIGHTS, DRAG AREAS AND COEFFICIENTS
      READ(5,1067)WSH,WSV,WSL,WTH,WCH,WAR,WBU,WLN,WMR,
     1ABU,ALN,AMR,AAR,
     2CDB,CDM,CDL,CDR
 1067 FORMAT (F10.5)
C     DRAG ABOVE STATION 1
      D=2.0*(CDB*ABU*(V(1)**2))
C     DRAG ON METER 1
      DM1=CDM*AMR*(V(1)**2)
C     DRAG ON LINE SECTION 1 WHEN NORMAL TO FLOW
      F(1)=CDL*ALN*20.0*(V(1)**2)
C     VERTICAL COMPONENT OF TENSION AT TOP OF LINE SECTION 1
      Y(1)=-2.0*WBU-4.0*WCH-8.0*WSH-WTH-WSL-WMR-WSV
C     HORIZ COMPONENT OF TENSION AT TOP OF LINE SECTION 1
      X(1)=DM1+D
C     WEIGHT OF LINE SECTION 1
      W(1)=20.0*WLN
```

```
C     ANGLE OF SECTION 1
      A(1)=ATAN((2.0*X(1)+F(1))/(2.0*Y(1)-W(1)))
C     HORIZ & VERT COMPONENTS OF TENSION AT TOP OF SECTION 2
      X(2)=X(1)+F(1)*((COS(A(1)))**3)
      Y(2)=Y(1)-W(1)-F(1)*((COS(A(1)))**2)*SIN(A(1))
C     SECTIONS 2 THROUGH 25
      DO 2000 I=2,24
      F(I)=CDL*ALN*20.0*(V(I)**2)
      W(I)=20.0*WLN
      A(I)=ATAN((2.0*X(I)+F(I))/(2.0*Y(I)-W(I)))
      CN=COS(A(I))
      SN=SIN(A(I))
      X(I+1)=X(I)+F(I)*(CN**3)
      Y(I+1)=Y(I)-W(I)-F(I)*(CN**2)*SN
 2000 CONTINUE
      DO 2002 I=1,24
      XAV(I)=(X(I)+X(I+1))/2.0
      YAV(I)=(Y(I)+Y(I+1))/2.0
      TAV(I)=(XAV(I)**2+YAV(I)**2)**.5000
 2002 CONTINUE
C     CORRECTIONS TO TENSION COMPONENTS AT TOP OF SECTION 25
      X(25)=X(25)+CDM*AMR*(V(25)**2)
      Y(25)=Y(25)-WMR-2.0*WTH-3.0*WSH-WSV-WSL
C     SECTIONS 25 THROUGH 45
      DO 2010 I=25,44
      F(I)=CDL*ALN*25.0*(V(I)**2)
      W(I)=25.0*WLN
      A(I)=ATAN((2.0*X(I)+F(I))/(2.0*Y(I)-W(I)))
      CN=COS(A(I))
      SN=SIN(A(I))
      X(I+1)=X(I)+F(I)*(CN**3)
      Y(I+1)=Y(I)-W(I)-F(I)*(CN**2)*SN
 2010 CONTINUE
      DO 2012 I=25,44
      XAV(I)=(X(I)+X(I+1))/2.0
      YAV(I)=(Y(I)+Y(I+1))/2.0
      TAV(I)=(XAV(I)**2+YAV(I)**2)**.5000
 2012 CONTINUE
C     CORRECTIONS TO TENSION COMPONENTS AT TOP OF SECTION 45
      X(45)=X(45)+CDM*AMR*(V(45)**2)+CDR*AAR*(V(45)**2)
      Y(45)=Y(45)-2.0*WTH-WMR-4.0*WSH-WSV-WAR-WSL
C     SECTIONS 45 TO BOTTOM OF 64
      DO 2020 I=45,64
      F(I)=CDL*ALN*33.0*(V(I)**2)
      W(I)=33.0*WLN
      A(I)=ATAN((2.0*X(I)+F(I))/(2.0*Y(I)-W(I)))
      CN=COS(A(I))
      SN=SIN(A(I))
      X(I+1)=X(I)+F(I)*(CN**3)
      Y(I+1)=Y(I)-W(I)-F(I)*(CN**2)*SN
 2020 CONTINUE
C     CHAIN AND ITS HARDWARE WEIGHT CORRECTIONS TO VERT TENSION
C     ON ANCHOR
      Y(65)=Y(65)-WCH*10.0-WSV-3.0*WSH-WTH
```

```
C     HORIZ AND VERT TENSION COMPONENTS ON ANCHOR DUE TO CURRENT
C     METER ARRAY
      ANCHX=X(65)
      ANCHY=Y(65)
      TANCH=(ANCHX**2+ANCHY**2)**.5000
C     AVG TENSION IN EACH LINE SECTION
      DO 2050 I=45,64
      XAV(I)=(X(I)+X(I+1))/2.0
      YAV(I)=(Y(I)+Y(I+1))/2.0
      TAV(I)=(XAV(I)**2+YAV(I)**2)**.5000
 2050 CONTINUE
C     UNSTRETCHED LENGTHS OF SECTIONS
      DO 2060 J=1,24
      S(J)=20.0
 2060 CONTINUE
      DO 2070 J=25,44
      S(J)=25.0
 2070 CONTINUE
      DO 2080 J=45,64
      S(J)=33.0
 2080 CONTINUE
C     ELONGATION CALCULATIONS BASED ON MFGR SPECIFIED ELASTIC
C     PROPERTIES OF POLYPROPYLENE LINE. E(I) IS FRACTION OF
C     ELONGATION. SS(I) IS STRETCHED SECTION LENGTH. E(I) EQUATION
C     HOLDS FOR TENSION GREATER THAN 135 LBS AND LESS THAN 540 LBS.
      DO 3000 I=1,64
      E(I)=.040+.000148*TAV(I)
      SS(I)=S(I)+S(I)*E(I)
 3000 CONTINUE
C     STARTING AT BOTTOM, A SET OF POINTS AT LINE SECTION JUNCTIONS
C     TO DESCRIBE CABLE SHAPE AND DIP AND EXCURSION CALCULATIONS.
      YY(1)=SS(64)*COS(A(64))
      XX(1)=SS(64)*SIN(A(64))
      DO 3030 I=1,63
      YC(I)=SS(64-I)*COS(A(64-I))
      XC(I)=SS(64-I)*SIN(A(64-I))
      YY(I+1)=YY(I)+YC(I)
      XX(I+1)=XX(I)+XC(I)
 3030 CONTINUE
C     METER LOCATIONS
      XM(1)=XX(64)
      YM(1)=YY(64)
      XM(2)=XX(40)
      YM(2)=YY(40)
      XM(3)=XX(20)
      YM(3)=YY(20)
C     ARRAY FOR GRAPH TITLE
      READ(5,3050)(ITITLE(I),I=1,12)
 3050 FORMAT (6A8)
      CALL DRAW(65,VV,Z,0,0,LABEL1,ITITLE,0,0,0,0,0,0,8,15,1,0)
      CALL DRAW(64,XX,YY,1,0,LABEL2,ITITLE,0,0,0,0,0,0,8,15,1,0)
      CALL DRAW(3,XM,YM,3,5,LABEL3,ITITLE,0,0,0,0,0,0,8,15,1,0)
      WRITE(6,4000)
 4000 FORMAT('1',10X,'CURRENT METER ARRAY MOORING DATA',//,
     1'0','LINE SECT',5X,'AVG CURR SPD',5X,'ANGLE',5X,'UNSTRETCHED',
```

```
     25X,'STRETCHED',5X,'AVG TENSION')
      DO 4010 I=1,64
      AA(I)=57.3*A(I)
      WRITE(6,4015)I,V(I),AA(I),S(I),SS(I),TAV(I)
 4010 CONTINUE
 4015 FORMAT('0',3X,I2,9X,F12.4,3X,F9.4,3X,F11.4,5X,F9.4,5X,F11.4)
      WRITE(6,4020)
 4020 FORMAT ('1','CURRENT METER NO',5X,'Z FOR NO STRETCH NO DRAG',
     15X,'Z FOR CONDITIONS',5X,'X FOR CONDITIONS')
      ZA(1)=Z(1)
      ZA(2)=Z(25)
      ZA(3)=Z(45)
      DO 4030 I=1,3
      ZB(I)=1800.0-YM(I)
      WRITE(6,4035)I,ZA(I),ZB(I),XM(I)
 4030 CONTINUE
 4035 FORMAT ('0',7X,I2,13X,F24.4,5X,F16.4,5X,F16.4)
      WRITE(6,4060)ANCHX,ANCHY
 4060 FORMAT ('0','HORIZ AND VERT FORCES ON ANCHOR ARE',F15.4,5X,
     1F15.4)
      WRITE(6,4070)TANCH
 4070 FORMAT ('0','RESULTANT FORCE ON ANCHOR =',F15.4)
      STOP
      END
```

"REEL" PROGRAM

```
C     PROGRAM TO COMPUTE APPROXIMATE CONFIGURATION OF SUBSURFACE MOORED
C     CURRENT METER ARRAY UNDER INFLUENCE OF CURRENT. PROGRAM WILL
C     SELECT LINE LENGTHS, PRODUCE PLOTS OF MOORING CONFIGURATIONS AND
C     CURRENT PROFILES, AND WILL COMPUTE VARIOUS IMPORTANT PARAMETERS
C     OF THE ARRAY.
      REAL*8 ITITLE(12)
      REAL LABEL1/'VELO'/,LABEL2/'MOOR'/,LABEL3/'MOOR'/
      DIMENSION Z(65),V(64),F(64),Y(65),X(65),W(64),A(64),
     1XAV(64),YAV(64),TAV(64),S(64),SS(64),E(64),YY(64),XX(64),
     2YC(64),XC(64),XM(3),YM(3),ZA(3),ZB(3),AA(64),VV(1800),
     3MI(64),VD(72),ZD(72)
C     COMPONENTS IN-WATER WEIGHTS, DRAG AREAS AND COEFFICIENTS
      READ(5,1067)WSH,WSV,WSL,WTH,WCH,WAR,WBU,WLN,WMR,
     1ABU,ALN,AMR,AAR,
     2CDB,CDM,CDL,CDR
 1067 FORMAT (F10.5)
C     ARRAY FOR GRAPH TITLE
      READ(5,3050)(ITITLE(I),I=1,12)
 3050 FORMAT (6A8)
C     VALUES OF ASSUMED CURRENT PROFILE AT DEPTH BELOW
C     SEA LEVEL IN FEET PER SECOND
      DO 1030 I=1,500
      VV(I)=1.2*1.69
 1030 CONTINUE
      DO 1040 I=501,690
      VV(I)=(1.2-(.7/190.0)*(FLOAT(I)-500.0))*1.69
 1040 CONTINUE
      DO 1050 I=691,1800
      VV(I)=(.500-(.3/1110.0)*(FLOAT(I)-690.0))*1.69
 1050 CONTINUE
C     IF TOP METER DOES NOT COME WITHIN 30 FEET OF BEING AT
C     160-FOOT DEPTH UNDER CURRENT CONDITIONS SPECIFIED
C     THE K-LOOP EXTENDS THE LENGTH OF ALL UNSTRETCHED LINE
C     BY 1 PERCENT.
      M=1
      N=12
C     VELOCITY PROFILE LOOP
      DO 5000 L=1,6
C     LINE EXTENSION LOOP
      DO 3035 K=M,N
      P=.010*FLOAT(K-1)
C     POINTS FOR PLOTTING VELOCITY PROFILE
      DO 1025 I=1,72
      ZD(I)=FLOAT(I*25)
      VD(I)=VV(I*25)
 1025 CONTINUE
C     DEPTH OF EACH STATION IS COMPUTED FOR NO STRETCH, NO DRAG.
      DO 1000 I=1,25
      Z(I)=(20.0+P*20.0)*FLOAT(I-1)+160.0-P*16.40*100.0
 1000 CONTINUE
      DO 1010 I=26,45
      Z(I)=(25.0+P*25.0)*FLOAT(I-25)+640.0-P*11.60*100.0
```

```
 1010 CONTINUE
      DO 1020 I=46,65
      Z(I)=(33.0+P*33.0)*FLOAT(I-45)+1140.0-P*6.60*100.0
 1020 CONTINUE
C     CURRENT FOR EACH LINE SECTION
      DO 1060 J=1,64
      MI(J)=IFIX(Z(J))
 1060 CONTINUE
C     ALL V(J) BELOW ARE EQUIVALENT VELOCITIES. SEE DISCUSSION.
      DO 1062 J=1,24
      NM=MI(J)
      NM2=MI(J)+20
      V(J)=((VV(NM)**2+VV(NM)*VV(NM2)+VV(NM2)**2)/3.0)**.500
 1062 CONTINUE
      DO 1063 J=25,44
      NM=MI(J)
      NM2=MI(J)+25
      V(J)=((VV(NM)**2+VV(NM)*VV(NM2)+VV(NM2)**2)/3.0)**.500
 1063 CONTINUE
      DO 1064 J=45,64
      NM=MI(J)
      NM2=MI(J)+33
      V(J)=((VV(NM)**2+VV(NM)*VV(NM2)+VV(NM2)**2)/3.0)**.500
 1064 CONTINUE
C     DRAG ABOVE STATION 1
      D=2.0*(CDB*ABU*(V(1)**2))
      D=D-D/2.0
C     DRAG ON METER 1
      DM1=CDM*AMR*(V(1)**2)
C     DRAG ON LINE SECTION 1 WHEN NORMAL TO FLOW
      F(1)=CDL*ALN*(20.0+P*20.0)*(V(1)**2)
C     VERTICAL COMPONENT OF TENSION AT TOP OF LINE SECTION 1
      Y(1)=-2.0*WBU-4.0*WCH-8.0*WSH-WTH-WSL-WMR-WSV
      Y(1)=Y(1)+WBU+4.0*WCH+4.0*WSH
C     HORIZ COMPONENT OF TENSION AT TOP OF LINE SECTION 1
      X(1)=DM1+D
C     WEIGHT OF LINE SECTION 1
      W(1)=(20.0+P*20.0)*WLN
C     ANGLE OF SECTION 1
      A(1)=ATAN((2.0*X(1)+F(1))/(2.0*Y(1)-W(1)))
      A(1)=ATAN((2.0*X(1)+F(1)*COS(A(1)))/(2.0*Y(1)-W(1)))
      A(1)=ATAN((2.0*X(1)+F(1)*COS(A(1)))/(2.0*Y(1)-W(1)))
C     HORIZ & VERT COMPONENTS OF TENSION AT TOP OF SECTION 2
      X(2)=X(1)+F(1)*((COS(A(1)))**3)
      Y(2)=Y(1)-W(1)-F(1)*((COS(A(1)))**2)*SIN(A(1))
C     SECTIONS 2 THROUGH 25
      DO 2000 I=2,24
      F(I)=CDL*ALN*(20.0+P*20.0)*(V(I)**2)
      W(I)=(20.0+P*20.0)*WLN
      A(I)=ATAN((2.0*X(I)+F(I))/(2.0*Y(I)-W(I)))
      A(I)=ATAN((2.0*X(I)+F(I)*COS(A(I)))/(2.0*Y(I)-W(I)))
      A(I)=ATAN((2.0*X(I)+F(I)*COS(A(I)))/(2.0*Y(I)-W(I)))
      CN=COS(A(I))
      SN=SIN(A(I))
```

```
      X(I+1)=X(I)+F(I)*(CN**3)
      Y(I+1)=Y(1)-W(I)-F(I)*(CN**2)*SN
 2000 CONTINUE
      DO 2002 I=1,24
      XAV(I)=(X(I)+X(I+1))/2.0
      YAV(I)=(Y(I)+Y(I+1))/2.0
      TAV(I)=(XAV(I)**2+YAV(I)**2)**.5000
 2002 CONTINUE
C     CORRECTIONS TO TENSION COMPONENTS AT TOP OF SECTION 25
      X(25)=X(25)+CDM*AMR*(V(25)**2)
      X(25)=X(25)+CDB*ABU*(V(25)**2)
      Y(25)=Y(25)-WMR-2.0*WTH-3.0*WSH-WSV-WSL
      Y(25)=Y(25)-WBU-2.0*WSH
C     SECTIONS 25 THROUGH 45
      DO 2010 I=25,44
      F(I)=CDL*ALN*(25.0+P*25.0)*(V(I)**2)
      W(I)=(25.0+P*25.0)*WLN
      A(I)=ATAN((2.0*X(I)+F(I))/(2.0*Y(I)-W(I)))
      A(I)=ATAN((2.0*X(I)+F(I)*COS(A(I)))/(2.0*Y(I)-W(I)))
      A(I)=ATAN((2.0*X(I)+F(I)*COS(A(I)))/(2.0*Y(I)-W(I)))
      CN=COS(A(I))
      SN=SIN(A(I))
      X(I+1)=X(I)+F(I)*(CN**3)
      Y(I+1)=Y(I)-W(I)-F(I)*(CN**2)*SN
 2010 CONTINUE
      DO 2012 I=25,44
      XAV(I)=(X(I)+X(I+1))/2.0
      YAV(I)=(Y(I)+Y(I+1))/2.0
      TAV(I)=(XAV(I)**2+YAV(I)**2)**.5000
 2012 CONTINUE
C     CORRECTIONS TO TENSION COMPONENTS AT TOP OF SECTION 45
      X(45)=X(45)+CDM*AMR*(V(45)**2)+CDR*AAR*(V(45)**2)
      Y(45)=Y(45)-2.0*WTH-WMR-4.0*WSH-WSV-WAR-WSL
C     SECTION 45 TO BOTTOM OF 64
      DO 2020 I=45,64
      F(I)=CDL*ALN*(33.0+P*33.0)*(V(I)**2)
      W(I)=(33.0+P*33.0)*WLN
      A(I)=ATAN((2.0*X(I)+F(I))/(2.0*Y(I)-W(I)))
      A(I)=ATAN((2.0*X(I)+F(I)*COS(A(I)))/(2.0*Y(I)-W(I)))
      A(I)=ATAN((2.0*X(I)+F(I)*COS(A(I)))/(2.0*Y(I)-W(I)))
      CN=COS(A(I))
      SN=SIN(A(I))
      X(I+1)=X(I)+F(I)*(CN**3)
      Y(I+1)=Y(I)-W(I)-F(I)*(CN**2)*SN
 2020 CONTINUE
C     CHAIN AND ITS HARDWARE WEIGHT CORRECTIONS TO VERTICAL TENSION
C     ON ANCHOR
      Y(65)=Y(65)-WCH*10.0-WSV-3.0*WSH-WTH
C     HORIZ AND VERT TENSION COMPONENTS ON ANCHOR DUE TO CURRENT
C     METER ARRAY
      ANCHX=X(65)
      ANCHY=Y(65)
      TANCH=(ANCHX**2+ANCHY**2)**.5000
C     AVG TENSION IN EACH LINE SECTION
```

```
      DO 2050 I=45,64
      XAV(I)=(X(I)+X(I+1))/2.0
      YAV(I)=(Y(I)+Y(I+1))/2.0
      TAV(I)=(XAV(I)**2+YAV(I)**2)**.5000
 2050 CONTINUE
C     UNSTRETCHED LENGTHS OF SECTIONS
      DO 2060 J=1,24
      S(J)=20.0+P*20.0
 2060 CONTINUE
      DO 2070 J=25,44
      S(J)=25.0+P*25.0
 2070 CONTINUE
      DO 2080 J=45,64
      S(J)=33.0+P*33.0
 2080 CONTINUE
C     ELONGATION CALCULATIONS BASED ON MFGR SPECIFIED ELASTIC
C     PROPERTIES OF POLYPROPYLENE LINE. E(I) IS FRACTION OF
C     ELONGATION. SS(I) IS STRETCHED SECTION LENGTH. E(I) EQUATION
C     HOLDS FOR TENSION GREATER THAN 135 LBS AND LESS THAN 540 LBS.
      DO 3000 I=1,64
      E(I)=.040+.000148*TAV(I)
      SS(I)=S(I)+S(I)*E(I)
 3000 CONTINUE
C     STARTING AT BOTTOM, A SET OF POINTS AT LINE SECTION JUNCTIONS
C     TO DESCRIBE CABLE SHAPE AND DIP AND EXCURSION CALCULATIONS
      YY(1)=SS(64)*COS(A(64))
      XX(1)=SS(64)*SIN(A(64))
      DO 3030 I=1,63
      YC(I)=SS(64-I)*COS(A(64-I))
      XC(I)=SS(64-I)*SIN(A(64-I))
      YY(I+1)=YY(I)+YC(I)
      XX(I+1)=XX(I)+XC(I)
 3030 CONTINUE
C     METER LOCATIONS
      XM(1)=XX(64)
      YM(1)=YY(64)
      XM(2)=XX(40)
      YM(2)=YY(40)
      XM(3)=XX(20)
      YM(3)=YY(20)
      MM=K
      ZM1=1800.0-YM(1)
      IF(ZM1.LE.190.0)GO TO 3049
 3035 CONTINUE
 3049 B=3.00E-01
      C=2.00E 02
      G=1.00E 02
      CALL DRAW(72,VD,ZD,0,0,LABEL1,ITITLE,B,C,0,0,0,0,9,9,1,0)
      CALL DRAW(64,XX,YY,1,0,LABEL2,ITITLE,G,C,0,0,0,0,9,9,1,0)
      CALL DRAW(3,XM,YM,3,5,LABEL3,ITITLE,G,C,0,0,0,0,9,9,1,0)
      WRITE(6,4000)
 4000 FORMAT('1',10X,'CURRENT METER ARRAY MOORING DATA',//,
     1'0','LINE SECT',5X,'EQUIV VELCTY',5X,'ANGLE',5X,'UNSTRETCHED',
     25X,'STRETCHED',5X,'AVG TENSION')
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```
      DO 4010 I=1,64
      AA(I)=57.3*A(I)
      WRITE(6,4015)I,V(I),AA(I),S(I),SS(I),TAV(I)
 4010 CONTINUE
 4015 FORMAT ('0',3X,I2,9X,F12.4,3X,F9.4,3X,F11.4,5X,F9.4,5X,F11.4)
      WRITE(6,4020)
 4020 FORMAT('0'.'CURRENT METER NO',5X,'Z FOR NO STRETCH NO DRAG',
     15X,'Z FOR CONDITIONS',5X,'X FOR CONDITIONS')
      ZA(1)=Z(1)
      ZA(2)=Z(25)
      ZA(3)=Z(45)
      DO 4030 I=1,3
      ZB(I)=1800.0-YM(I)
      WRITE(6,4035)I,ZA(I),ZB(I),XM(I)
 4030 CONTINUE
 4035 FORMAT ('0',7X,I2,13X,F24.4,5X,F16.4,5X,F16.4)
      WRITE(6,4060)ANCHX,ANCHY
 4060 FORMAT ('0','HORIZ AND VERT FORCES ON ANCHOR ARE',F15.4,5X,
     1F15.4)
      WRITE(6,4070)TANCH
 4070 FORMAT ('0','RESULTANT FORCE ON ANCHOR =',F15.4)
      WRITE(6,4080)P
 4080 FORMAT ('0','FRACTION THAT ALL UNSTRETCHED LINE HAD TO BE
     1EXTENDED OVER INITIAL SECTION LENGTHS IS',F8.4)
C      SEEING  BEHAVIOR OF ARRAY UNDER OTHER CURRENT PROFILES
      IF(L.EQ.6)GO TO 5100
      GO TO(4085,4087,4089,4092,4094),L
C     CURRENT 80 PERCENT OF ORIGINAL PROFILE
 4085 DO 4086 I=1,1800
      VV(I)=.80*VV(I)
 4086 CONTINUE
      GO TO 4098
C     CURRENT 40 PERCENT OF ORIGINAL PROFILE
 4087 DO 4088 I=1,1800
      VV(I)=.50*VV(I)
 4088 CONTINUE
      GO TO 4098
C     CURRENT 20 PERCENT OF ORIGINAL PROFILE
 4089 DO 4091 I=1,1800
      VV(I)=.50*VV(I)
 4091 CONTINUE
      GO TO 4098
C     CURRENT 10 PERCENT OF ORIGINAL PROFILE
 4092 DO 4093 I=1,1800
      VV(I)=.50*VV(I)
 4093 CONTINUE
      GO TO 4098
C     CURRENT 5 PERCENT OF ORIGINAL PROFILE
 4094 DO 4095 I=1,1800
      VV(I)=.50*VV(I)
 4095 CONTINUE
 4098 M=MM
      N=MM
 5000 CONTINUE
 5100 STOP
      END
```

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13. ABSTRACT

A study was conducted to select and design the optimum mooring system for positioning a three-instrument current meter array in 1800 feet of water off the California coast. A U-style mooring system was selected; the U-style mooring isolates the instruments from surface waves and offers three separate methods of instrument recovery. The mooring was designed and the various components to be used in its construction were specified. Computer analysis was used to approximate the theoretical static profile of the instrument array under the influence of current. An array of two instruments was stationed in 47 fathoms in Monterey Bay to test the basic design of the system. The mooring system was found to be suitable for safe and efficient deployment and recovery from R/V ACANIA.

14. KEY WORDS	LINK A		LINK B		LINK C	
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